THIRD EDITION

APPLIED WELDING ENGINEERING

PROCESSES, CODES, AND STANDARDS

RAMESH SINGH

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Processes, Codes, and Standards

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Ramesh Singh

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This book is dedicated to the memory of Sgt. S.A. Siddique of the Indian Air Force. I am eternally grateful to Sgt. Siddique for instilling the seeds of metallurgy and welding engineering in my mind, training of thought processing, and inspiring hard work; this book is just a small gratitude to the great teacher.

Preface to the first edition

There are several books in the market that strictly address the needs of academia. Some others address specific topics and are aimed at that particular segment of readers who are aware of the subject matter but are in search of new perspectives or new findings.

This book, *Applied Welding Engineering: Processes, Codes, and Standards*, aims to bridge the gap left by two segments described earlier. This intends to support the undersupported, by giving a practical perspective to the theoretical texts. Students trying to steer through the terminologies of the field, balancing theory with the practical side of welding engineering, will find this book useful in bridging that gap. The objective is to keep budding engineers moored in the theory taught in the university and collages while exploring the real world of practical welding engineering. The book is also aimed at those engineers, nonengineers, managers, and inspectors to serve as a body of knowledge and source of reference.

In writing this book, I do not claim originality on all thoughts and words. On a universal subject such as welding engineering, no single source can claim originality of thought. A lot of information contained in this book comes from my personal experiences and also from several industry publications such as those of American Society of Mechanical Engineers (www.asme.org), American Welding Society (www.aws.org), American Society of Metals (www.asminternational.org), NACE International (www.nace.org), American Petroleum Institute (www.api.org), and several training manuals including The Welding Institute, United Kingdom (www.twi.co.uk), and Indian Air Force training manuals, ASNT (www.asnt.org), the Canadian Standard Association (www.cas.com) and Canadian General Standard Board (CGSB) (www.tpsgc-pwgsc.gc.ca) trainings, just to name a few. It is not possible for me to distinguish which part of my experience is gained from which specific source, but I cannot deny their combined contribution in developing my knowledge base over the years. I acknowledge them all, and I am proud of that. Where I have consciously borrowed matters and ideas directly from these sources, I have acknowledged them as best as I could and appreciate the great service these bodies have rendered to welding engineering.

Individuals who need more detailed study on any specific topic covered in this book should reach out to these specialized associations and institutions for further guidance. Several published works are available from these bodies that can be of help in developing in-depth understanding of specific subjects.

Preface to the second edition

The second edition has updated some of the welding processes such as the square wave arc power source on newer variants of the gas metal arc-welding process. Some real-life case studies about welding-specific materials, such as low-alloy and high-strength low-alloy steels (HSLA), and in specific service conditions, such as low-temperature application and high-temperature hydrogen attack, have also been added. This edition also contains the quality assurance aspect of welding and fabrication with the addition of several European Norm and International Organization for Standardization specifications in the section describing various specifications related to welding and its quality assurance.

Preface to the third edition

In this edition, I have corrected some of phrases and sentences that were grammatically misplaced or incorrectly printed; these corrections are not such that would change the subject matter in any way. The major change in this edition is the addition of a new chapter. Readers' feedback and experience told me that I needed to include more detail about automation of welding processes. The automation and mechanization of the welding process is extensively used where repeated welding action takes place, as in manufacturing industries, and also in some not so repetitive fabrication activities, as in pipeline welding, pressure vessels, and tank manufacturing. And with automization has come use of robots. In the third edition of the book, I have taken help from Joel Troyer PE, CWI, senior welding engineer with several years of experience in the field and use of automatic welding processes. Joel has contributed to the new chapter about automatic welding, wherein he also delves into robotics to explain the various degrees of freedom and movements achieved for welding in different positions as is encountered in the fabrication process. Joel Troyer is a Professional Engineer in Texas, and a graduate from LeTourneau University with a degree in Engineering with Welding and Mechanical Engineering concentration.

Acknowledgments

Writing this book made me realize how dependent a person is in accomplishing a task of this nature. The process started with retrieving several years of notes, handouts, and handwritten charts, some as old as from 1969. Some of them had turned yellow and torn, stained of sweat and dirt, possibly of physical punishments that were liberally given to us student in Air Force Institute. Some of the papers were torn at the folds; tape was used to save them until I had used the information contained in them.

I am extremely grateful to several of my clients and employers for creating an environment that encouraged me to write the first edition of this book. I am especially grateful to the late James McLane Jr. III, my friend and colleague at Gulf Interstate Engineering (www.gie.com) who encouraged me to take up this project. I am also indebted for the encouragement, support, and help from my friend Olga Ostrovsky. She helped me negotiate the obstacles of writing and editing the drafts. Without her expert help, this book would not be possible.

Last but not least, I am also grateful to my loving wife Mithilesh and my son Sitanshu for their support in accomplishing this goal. Mithilesh tolerated my indulgence with the project. Without her support and understanding, this task was not possible.

Finally a few words on dedication of this book, I have dedicated this book to Sergeant S.A. Siddique of the Indian Air Force. Sgt. Siddique taught me the first lessons of metallurgy and welding engineering. Drawing on my Indian ethos, I know the protocol, “Teacher takes precedence even over God,” hence the education.

Section 1

Introduction to Basic Metallurgy

Introduction

1

When we talk of metallurgy as a science of the study of metals, the first question that arises in the mind is “What is a metal?” Most of us can recall the introductory study of metals in basic physics in school.

Metals are best described by their properties. Metals are crystalline in the solid state. Except for mercury, metals are solid at room temperature; mercury is a metal but in liquid form at room temperature. Metals are good conductors of heat and electricity, and they usually have comparatively high density. Most metals are ductile, a property that allows them to be shaped and changed permanently without breaking by the application of relatively high forces. Metals are elements, and metal are also alloys created by man in pursuit of specific properties. Aluminum, iron, copper, gold, and silver are examples of metals as elements, and brass, steel, bronze, etc. are examples of alloys, the man-made metals.

Metallurgy is the science and technology of metals and alloys. The study of metallurgy can be divided into three general groups:

1. Process metallurgy

   Process metallurgy is concerned with the extraction of metals from their ores and the refining of metals. A brief discussion on production of steel, castings, and aluminum is included in this section.
2. Physical metallurgy

   Physical metallurgy is concerned with the physical and mechanical properties of metals affected by composition processing and environmental conditions. A number of chapters in this section specifically address this topic.
3. Mechanical metallurgy

   Mechanical metallurgy is concerned with the response of metals to applied forces. This is addressed in subsequent chapters of this section.

Pure metals and alloys

Pure metals are soft, weak, and used only for specialty purposes such as laboratory research work and electroplating. Foreign elements (metallic or nonmetallic) that are always present in any metal may have beneficial, detrimental, or no influence on a particular property. Whereas disadvantageous foreign elements are called *impurities*, advantageous foreign elements are called *alloying elements*. When alloying elements are deliberately added, the resulting metal is called an *alloy*. Alloys are grouped and identified by their primary element metal, e.g., aluminum alloy, iron alloy, copper alloy, nickel alloy, and so on.

Most of the metals as elements are not found in nature in their usable form. They are generally found in their various oxide forms called *ores*. The metals are recovered from these ores by thermal and chemical reactions. We shall briefly discuss some

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of these processes. The most common and abundantly used metal is iron, and its recovery from nature by various means is discussed in the following paragraphs.

Smelting

Smelting is an energy intensive process used to refine an ore into a usable metal. Most ore deposits contain metals in a reacted or combined form, such as magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite ($\alpha FeO(OH)$), limonite (generic formula for limonite is $FeO(OH) \cdot nH_2O$), and siderite ($FeCO_3$), which are iron ores, and Cu_5FeSO_4, which is a copper ore. The smelting process melts the ore, usually for a chemical change to separate the metal, thereby reducing or refining it. The smelting process requires a lot of energy to extract the metal from the other elements.

There are other methods of extraction of pure metals from their ore. Some of these use an application of heat, leaching in a strong acidic or alkaline solution, or by electrolytic processes.

Iron

The modern production processes for recovery of iron from ore includes blast furnaces to produce pig iron, which contains carbon, silicon, manganese, sulfur, and phosphorous, and many other elements and impurities. Unlike wrought iron, pig iron is hard, brittle, and cannot be hammered into a desired shape. Pig iron is the basis of a majority of steel production. A majority of steel produced in the world is created through pig iron production.

Sponge iron

Removing oxygen from the ore by a natural process produces a relatively small percentage of steels in the world. This process uses less energy and is a natural chemical reaction method. The process involves heating the naturally occurring iron oxide in the presence of carbon, which produces "sponge iron." In this process, the oxygen is removed without melting the ore.

Iron oxide ores extracted from the Earth are allowed to absorb carbon by a reduction process. In this natural reduction reaction, as the iron ore is heated with carbon, it results in a pop-marked surface, hence the name "sponge iron." The commercial process is a solid solution reduction, also called *direct-reduced iron (DRI)*. In this process, the iron ore lumps, pellets, or fines are heated in a furnace at 800–1500°C (1470–2730°F) in a carburizing environment. A reducing gas produced by natural gas or coal, and a mixture of hydrogen and carbon monoxide gas, provides the carburizing environment.

The resulting sponge iron is hammered into shapes to produce wrought iron. The conventional integrated steel plants of less than one million tons annual capacity are generally not economically viable, but some of the smaller capacity steel plants use sponge iron as a charge to convert iron into steel. Because the reduction process of sponge iron is not energy intensive, the steel mills find it a more environmentally acceptable process. The process also tends to reduce the cost of steelmaking. The negative aspect of the process is that it is slow and does not support large-scale steel production.

Iron alloys that contain 0.1% and 2% carbon are designated as steels. Iron alloys with greater than 2% carbon are called *cast irons*.

Alloys

2

Alloys

An alloy is a substance that has metallic properties and is composed of two or more chemical elements in which the primary one is a metal. A binary alloy system is a group of all alloys that can be formed by two elements combined in all possible proportions.

Homogeneous alloys consist of a single phase, and mixtures consist of several phases. A phase is anything that is homogeneous and physically distinct if viewed under a microscope. When an allotropic metal undergoes a change in crystal structure, it undergoes a phase change.

There are three possible phases in the solid state:

- Pure metal
- Intermediate alloy phase or compound
- Solid solution

Compounds have their own characteristic physical, mechanical, and chemical properties and exhibit definite melting and freezing points. Intermetallic compounds are formed between dissimilar metals by chemical valence rules and generally have nonmetallic properties; Mg_2Sn and Cu_2Se are examples of intermetallic compounds.

Interstitial compounds are formed between transition metals such as titanium and iron with hydrogen, oxygen, carbon, boron, and nitrogen. They are usually metallic with high melting points and are extremely hard; TiC, and Fe_3C are examples of interstitial compounds.

Electron compounds are formed from materials with similar lattice systems and have a definite ratio of valence electrons to atoms; Cu_3Si, and FeZn are examples of electron compounds.

Solid solutions are solutions in the solid state and consist of two kinds of atoms combined in one kind of space lattice. The solute atoms can be present in either a substitutional or an interstitial position in the crystal lattice.

There are three possible conditions for solid solution:

- Unsaturated
- Saturated
- Supersaturated

The solute is usually more soluble in the liquid state than in the solid state. Solid solutions show a wide range of chemistry, so they are not expressed by a chemical formula. Most solid solutions solidify over a range of temperature.

With a basic understanding of alloy formation and types of alloying, we move forward to learn about specific alloy steel and the effects of various alloying elements on steel properties.

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Effects of alloying elements

Carbon steels

Metals are alloyed for a specific purpose, generally with the aim of improving a specific property or a set of properties. To take full advantages of such alloying, it is important that the resulting property of alloying elements is known. In the following discussions, with the help of steel metallurgy, we shall learn some of the most common alloying practices and their resulting alloy metals.

Sulfur

Sulfur in steel is generally kept below 0.05% as it combines with iron to form FeS, which is a low-temperature melting alloy that tends to concentrate at grain boundaries. At elevated temperatures, high sulfur steel becomes hot-short due to melting of the FeS eutectic. In free-machining steels, the sulfur content is increased to 0.08% and 0.35%. The sulfide inclusions act as chip breakers, reducing tool wear.

Manganese

Manganese is present in all commercial carbon steels in the range of 0.03%–1.00%. Manganese functions to counteract sulfur by forming MnS, and any excess manganese combines with carbon to form the Mn_3C compound associated with cementite. Manganese also acts as a deoxidizer in the steel melt.

Phosphorous

Phosphorous in steel is kept below 0.04%. Presence of phosphorous over 0.04% reduces the steel's ductility, resulting in cold-shortness. Higher phosphorous from 0.07% to 0.12% is included in steels specifically developed for machining, to improve cutting properties of steel.

Silicon

Silicon is present in most steels in the 0.05%–0.3% range. Silicon dissolves in ferrite, increasing strength while maintaining ductility. Silicon promotes deoxidation in the molten steel through the formation of SiO_2, hence it is an especially important addition in castings.

Alloy steels

Plain carbon steel is satisfactorily used where strength and other property requirements are not severe and when high temperatures and corrosive environments are not a major factor in the selection of material. Alloy steels have characteristic properties different from plain carbon steel; this is due to some elements other than carbon that are added. Alloying elements are added to obtain several properties including:

- Increased hardenability
- Improved strength at ambient temperatures
- Improved mechanical properties at low and high temperatures
- Improved toughness
- Improved wear resistance
- Increased corrosion resistance
- Improved magnetic permeability or magnetic retentivity

There are two ways in which alloy elements are distributed in the main constituents of steel:

- Elements that dissolve in ferrite
- Elements that combine with carbon to form simple or complex carbides

The effect of alloying elements on ferrite

Nickel, aluminum, silicon, copper, and cobalt are the elements that largely dissolve in ferrite. Elements that dissolve in ferrite tend to increase the ferrite's strength by solid solution hardening.

Alloying elements change the critical temperature range, eutectoid point position, and location of the alpha (α) and gamma (γ) fields on the iron-iron carbide phase diagram. These changes affect the heat-treating requirements and final properties of alloys.

Effects of alloying elements on carbide

Carbide-forming elements that include elements like manganese, chromium, tungsten, molybdenum, vanadium, and titanium increase room temperature tensile properties because all carbides are hard and brittle. The order of increasing effectiveness is chromium, tungsten, vanadium, molybdenum, manganese, nickel, and silicon; of this, nickel and silicon do not form carbides. Complex carbides are sluggish and hard to dissolve. They act as growth inhibitors and often improve high temperature properties. Chromium and vanadium carbides are exceptionally hard and wear resistant.

Tempering temperatures are raised significantly and, in some cases, secondary hardening may occur with higher tempering temperatures due to the delayed precipitation of fine alloy carbides.

Some of the common and general use alloys are briefly discussed here.

Nickel Steels (2xx Series)

Nickel has unlimited solubility in γ-iron and is highly soluble in ferrite. It widens the range for successful heat treatment, retards the decomposition of austenite, and does not form carbides.

Nickel promotes the formation of very fine and tough pearlite at lower carbon contents. Thus, toughness, plasticity, and fatigue resistance are improved. Nickel alloys are used for high-strength structural steels in the as-rolled condition and for large forgings that cannot be hardened by heat treatment.

Nickel-Chromium Steels (3xx Series)

The effect of nickel on increasing toughness and ductility is combined with the effect of chromium on improving hardenability and wear resistance. The combined effect of these two alloying elements is often greater than the sum of their effects.

Manganese Steels (31x Series)

Manganese is one of the least expensive of alloying elements and is always present as a deoxidizer and to reduce hot-shortness. When the manganese content exceeds 0.80%, it acts as an alloying element to increase strength and hardness in high carbon steels. Fine-grained manganese steels have excellent toughness and strength.

Steels with greater than 10% manganese remain austenitic after cooling and are known as Hadfield manganese steel. After heat treatment, this steel has excellent toughness and wear resistance as well as high strength and ductility. Work hardening occurs as the austenite is strain hardened to martensite.

Molybdenum Steels (4xx Series)

Molybdenum has limited solubility in α- and γ-iron and is a strong carbide former. It has a strong effect on hardenability and increases high-temperature strength and hardness. Molybdenum alloys are less susceptible to temper brittleness. Chromium-molybdenum alloys (AISI 41xx) are relatively cheap and ductile, have good hardenability, and are weldable.

Chromium Steels (5xx Series)

Chromium forms both simple (Cr_7C_3 and Cr_4C) and complex carbides [$(FeCr)_3C$]. These carbides have high hardness and resist wear. Chromium is soluble up to about 13% in γ-iron and has unlimited solubility in ferrite. Chromium increases strength and toughness of the ferrite as well as improves high-temperature properties and corrosion resistance.

When chromium is properly proportioned and added for a specific purpose, the resulting purpose-specific alloys exhibit one or a combination of the following specific properties:

(1) Increase in strength
(2) Increase in toughness of the ferrite
(3) May improve high-temperature properties
(4) Increase in corrosion resistance

Physical metallurgy

3

In the last chapter, we were briefly introduced to the alloying process and familiarized with various alloys of steel. In this chapter, we turn to the fundamental physics of metallurgy.

In a solid state, the materials have a crystal structure, broadly defined as the arrangement of atoms or molecules. This arrangement at an atomic and molecular level is collectively called *microstructure of material*. The atomic or molecular arrangement may include abnormalities in the crystalline structure.

Crystal lattices

The three-dimensional network of imaginary lines connecting atoms is called the *space lattice*. A crystal is an arrangement in three dimensions of atoms or molecules in repetitive patterns. The smallest unit having the full symmetry of the crystal is called the *unit cell*, the edges of which form three axes: a, b, and c. The three-dimensional aggregation of unit cells in the crystal forms a space lattice, or Bravais lattice. Seven different systems of crystal are identified, and each system has a different set of axes. The unit cell edge length of each a, b, and c corresponds to the three axes. The corresponding faces of the unit cells are identified with capital letters A, B, and C. The interaxial angles α, β, and γ correspond to the faces A, B, and C, respectively. The interaxial angle and the edge lengths of unit cells are unique to each crystalline substance.

Crystal structure nomenclature

The seven crystal structures are listed in the following text. In the left column are the basic systems. When they associate with the 5 lattices, they combine to form the 14 different combinations in the right column. The basis for this combination is William B. Pearson's widely used Pearson symbols. The system uses small case letters to identify the crystal system and capital case letters to identify the space lattices. The Pearson symbols are given in the brackets.

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Triclinic, also called anorthic	Primitive	(*aP*)
Monoclinic	Primitive	(*mP*)
	Base-centered	(*mC*)
Orthorhombic	Primitive	(*oP*)
	Base-centered	(*oC*)
	Body-centered	(*ol*)
	Face-centered	(*oF*)
Tetragonal	Primitive	(*tP*)
	Base-centered	(*tl*)
Hexagonal	Primitive	(*hP*)
Rhombohedral[a]	Primitive	(*hR*)
Cubic	Primitive	(*cP*)
	Body-centered	(*cl*)
	Face-centered	(*cF*)

[a] Rhombohedral crystals are also described using hexagonal axes.

Most metals of engineering importance crystallize in either the cubic or hexagonal systems, in one of three space lattices.

1. Body-centered cubic (bcc).
   Chromium, tungsten, alpha (α)-iron, delta (δ)-iron, molybdenum, vanadium, and sodium exhibit this kind of lattice.
2. Face-centered cubic (fcc).
   This structure is more densely packed than bcc. Aluminum, nickel, copper, gold, silver, lead, platinum, and gamma (γ)-iron exhibit this kind of lattice.
3. Close-packed hexagonal.
   Magnesium, beryllium, zinc, cadmium, and hafnium exhibit this kind of lattice (Figure 1-3-1).

Solidification

Associated with alloying is the subject of solidification; we shall briefly discuss this in the following paragraphs.

Lever rule of solidification

The calculation of the equilibrium solidification according to the lever rule is a one-dimensional stepping calculation in which one of the variables, the temperature, is stepped. At each step, a single point equilibrium calculation is carried out. The result of the calculation is phase compositions, phase fractions, and enthalpies. Because complete diffusion is assumed for all phases, the calculation may be continued after the liquid phase has disappeared to determine changes in the solid phases.

The details of phase diagrams are discussed in Chapter 4 of this section of the book. However, it is important to clarify a few things related to the use of Lever law and then proceed with the discussion of solidification and constitutional cooling.

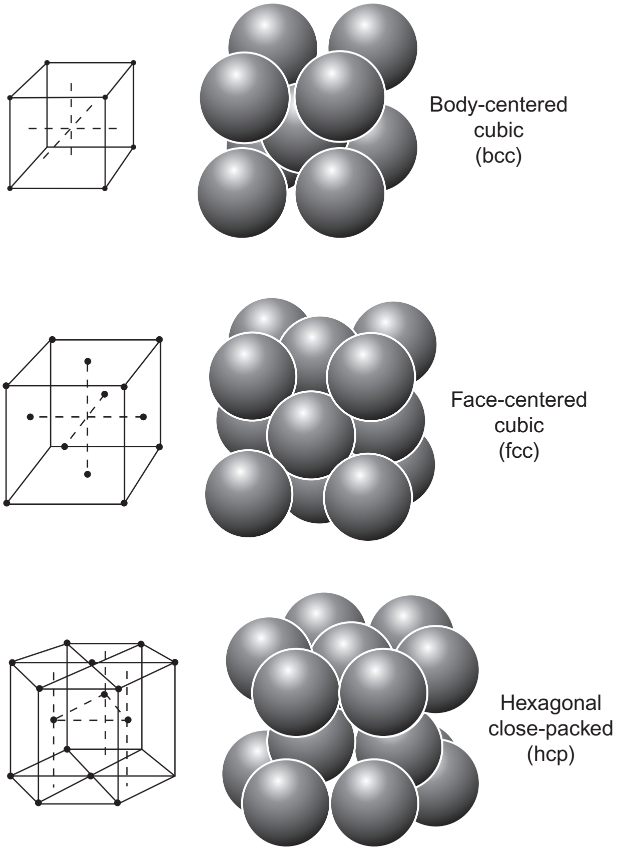


Figure 1-3-1 Crystal lattices.

One question that is often asked is, “What does a phase diagram give us?” Although we will learn the answer in Chapter 4, we will also consider the utility and importance of phase diagram in light of this question. This would include the determination of the amount or proportion of each phase present, and the evolution of the microstructure of the sample during cooling.

In alloys, there is unlimited solid solubility in both the liquid and solid phases, and the process of freezing (or melting) does not occur at a single fixed temperature, as happens with pure metallic elements. The freezing or melting in alloys takes place over a range of temperature points. At each temperature between the liquidus and solidus lines, the equilibrium structure is a mixture of the two (solid and liquid) phases, with the amounts and compositions of the phases fixed. These values can be determined from the phase diagram.

There are only two possibilities in any binary (two-component) alloy system. A point on the phase diagram may either lie within a single-phase field, in which there are two degrees of freedom, or the temperature and composition can be varied with no change in the microstructure. Single-phase fields are usually marked on phase diagrams with either a name or a Greek letter. This also explains why tie lines are not used in a single-phase alloy system.

Alternately, they may lie within a two-phase field, in which the proportion of the two phases will vary with composition or temperature changes. It is in these regions that the tie line is used, and the lever law is applied.

Thus, phase diagrams can be used to determine what phase or phases are present at a particular overall composition and temperature; this will be limited by the fact that, in a single-phase region, there is just one phase, and in a two-phase field, the ends of the tie line identify the presence of second phases.

The phase diagram also helps us understand what the compositions of the phases are. In a single-phase system, the information gives the bulk composition, whereas the two-phase system is defined by the tie line.

Another purpose of the phase diagram is that it also confirms that the single-phase system has 100% of the composition of one metal, which directs us to use Lever law equation to determine the proportional composition of metals in two-phase system.

Finally, the phase diagram tells us the arrangements of these phases in the microstructure as they develop during equilibrium (slow) cooling.

Thus, using Lever's equation we can determine the present phase(s) and their compositions at any given temperature. We can even slice the cooling process and determine the phase(s) and composition at any given point in the temperature range.

Constitutional supercooling

Solute is partitioned into a liquid of the solidification front. This causes a corresponding variation in the liquidus temperature, i.e., the temperature below which metal freezing begins. There is a positive temperature gradient in the liquid, giving rise to a supercooled zone of liquid ahead of the interface. This is called *constitutional supercooling* because it is caused by composition changes.

A small perturbation on the interface will therefore expand into a supercooled liquid. This gives rise to dendrites.

It follows that a supercooled zone only occurs when the liquidus temperature gradient at the interface is larger than the temperature gradient.

In practice, it is very difficult to avoid constitutional supercooling, because the required velocity is very small. Directional solidification with a planar front is possible only at low growth rates. A good example of this is the production of a single crystal of silicon. In most cases, the interface is unstable.

Mixing in a liquid is by convection, which reduces solute gradients in the liquid. The uniform composition throughout the solidification in the liquid is the exception to the rule.

A key phenomenon in solidification is the transfer of heat by radiation, direct contact with the mold (conduction), or through air movement via the air gap between the mold and ingot (convection). A casting situation may be divided depending on whether or not significant thermal gradients are set up in the solidifying metal.

When a liquid metal's temperature is dropped sufficiently below its freezing point, stable aggregates of atoms or nuclei appear spontaneously at various points in the liquid. These solid nuclei act as centers for further crystallization.

As cooling continues, more atoms attach themselves to already existing nuclei or form new nuclei. Crystal growth continues in three dimensions with the atoms attaching themselves in certain preferred directions along the axes of the crystal.

This forms the characteristic tree-like structure called a dendrite. Each dendrite grows in a random direction until finally the arms of the dendrites are filled, and further growth is obstructed by the neighboring dendrite. As a result, the crystals solidify in irregular shapes and are called *grains*.

The mismatched area along which crystals meet is called the *grain boundary*. It has a noncrystalline or amorphous structure with irregularly spaced atoms. Because of this irregularity, grain boundaries tend to be regions of high energy and reactions such as corrosion, and crack propagations are often associated with an affinity to grain boundary sites. Thus, nucleation is a major factor in determining the material's final properties.

Elementary theory of nucleation

Phase fluctuations occur as random events due to the thermal vibration of atoms. An individual fluctuation may or may not be associated with a reduction in free energy, but it can only survive and grow if there is a reduction. There is a cost associated with the creation of a new phase, the interface energy, a penalty that becomes smaller as the particle surface-to-volume ratio decreases. In a metastable system, this leads to a critical size of fluctuation beyond which growth is favored.

Let us consider a homogeneous nucleation of α from γ for a spherical particle of radius r with an isotropic interfacial energy $\sigma_{\alpha\gamma}$. The change in free energy (ΔG) as a function of radius is:

$$\Delta G = 1.33\,\pi r^3\,\Delta G_{CHEM} + 1.33\,\pi r^3\,\Delta G_{STRAIN} + 4\,\pi r^2\,\sigma_{\alpha\gamma} \qquad [1]$$

where:

$\Delta G_{CHEM} = G^{\alpha}v - G^{\gamma}v$, G_v is the Gibbs free energy per unit volume of α and G_{STRAIN} is the strain energy per unit volume of α.

The maximum variation in the curve of ΔG is determined by the differentiation of Equation [1] with respect to radius r:

$$\delta(\Delta G)/\delta r = 4\pi r^2\,[\Delta G_{CHEM} + \Delta G_{STRAIN}] + 8\pi r\sigma_{\alpha\gamma} \qquad [2]$$

In this equation, the value of r* is obtained by setting the value to zero:

$$r^* = 2\sigma_{\alpha\gamma}/\Delta G_{CHEM} + \Delta G_{STRAIN} \qquad [3]$$

By substitution of r* value in Equation [1], the activation energy is obtained as:

$$G^* = 16\pi\sigma^3{}_{\alpha\gamma}/3\,(\Delta G_{\mathrm{CHEM}} + \Delta G_{\mathrm{STRAIN}})^2 \qquad [4]$$

The key outcome is that, in classical nucleation, the activation energy varies inversely with the square of the driving force, and the mechanism involves random phase fluctuations. The nucleation rate per unit volume I_v will depend on the attempt frequency *v*, the number density of nucleation sites N_v, and the probability of successful attempts. There is also a barrier Q to the transfer of atoms across the interface:

$$I_v = N_v{}^{\nu} \exp\{-G^*/kT\} \exp\{Q/kT\} \qquad [5]$$

Allotropy

The property of some metals and alloys that exhibit different crystalline lattices at different temperatures is called *allotropy*. Allotropy is a very important property for materials; these allotropic changes are the basis for heat treatment of many engineering materials.

Iron and its alloys are the most common engineering materials that have allotropic forms. We will use this material as the basis of our discussion. Pure iron in its solid state has three allotropic forms: austenite (*y*), ferrite, and ε-iron. The latter has a hexagonal close-packed crystal structure, is the highest density state of iron, and is only stable at very large pressures. At ambient pressures, ferrite is stable at temperatures just below the equilibrium melting temperature (in which case, it is called δ-iron) and at relatively low temperatures as an α form of iron. Austenite is the stable form in the intervening temperature range between the δ and α. As was recognized a long time ago by Zener and others, this complicated (but useful) behavior is related to electronic and magnetic changes as a function of temperature.

The phase behavior of pure iron does not change radically with the addition of small amounts of solute, i.e., for low-alloy steels. For example, lightly alloyed steel weld deposits begin solidification with the epitaxial growth of delta-ferrite (δ) from the hot grain structure of the parent plate at the fusion boundary. The large temperature gradients at the solid/liquid interface ensure that solidification proceeds with a cellular front so that the final δ grains are columnar in shape, the major axes of the grains lying roughly along the direction of maximum heat flow. Upon further cooling, austenite allotriomorphs nucleate at the δ-ferrite grain boundaries, and their higher rate of growth along the δ-δ boundaries, and presumably along temperature gradients, leads to the formation of columnar austenite grains whose shape resembles that of the original solidification structure.

It is important to state here that cooling metallurgy is an important part of welding, as welding involves a moving heat source in which the orientation of the temperature isotherms alters with time. Consequently, the major growth direction of the austenite is found to be somewhat different from that of the δ grains.

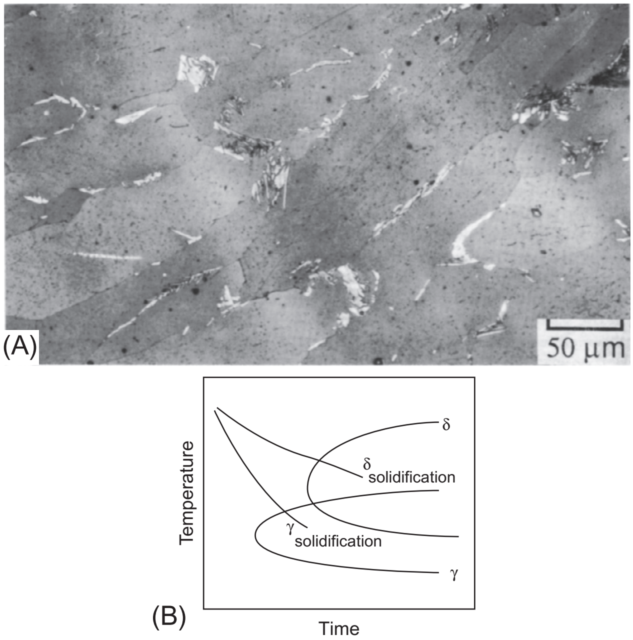


Figure 1-3-2 (A) Columnar δ ferrite grains, with austenite (light phase) allotriomorphs growing at the δ grain boundaries. (B) Schematic continuous cooling transformation diagram illustrating the solidification mode in low-alloy steels as a function of the cooling rate. Faster cooling rates can, in principle, lead to solidification and to metastable austenite.

If the cooling rate is large enough, then the liquid can be induced to solidify as metastable austenite as shown in Figure 1-3-2b. This could happen even when δ-ferrite is the thermodynamically favored phase in low-alloy steels. It has been suggested that this is especially likely when the partition coefficient $k = cS/cL$ is closer to unity for austenite than for ferrite. The cS and cL are the solute solubility in the solid and liquid phases, respectively. In those circumstances, the austenite growth rate can exceed that of δ-ferrite if the liquid is sufficiently undercooled. Solidification with austenite as the primary phase becomes more feasible as the steel is alloyed with austenite-stabilizing elements, until they eventually become the thermodynamically stable phase.

Solidification to austenite can be undesirable for two reasons; large inclusions tend to become preferentially trapped at the cusps in the advancing solid/liquid interface and end up at the columnar grain boundaries. When austenite forms directly from the liquid, the inclusions are located in the part of the weld that, in the final microstructure, corresponds to relatively brittle allotriomorphic ferrite. This is not the case with δ solidification because, during subsequent transformation, the daughter austenite grains cut across the δ/δ grain boundaries, leaving the large inclusions inside the grains where they can do less harm, and perhaps also be of use in stimulating the nucleation of acicular ferrite. The second reason to avoid solidification diffusion rate

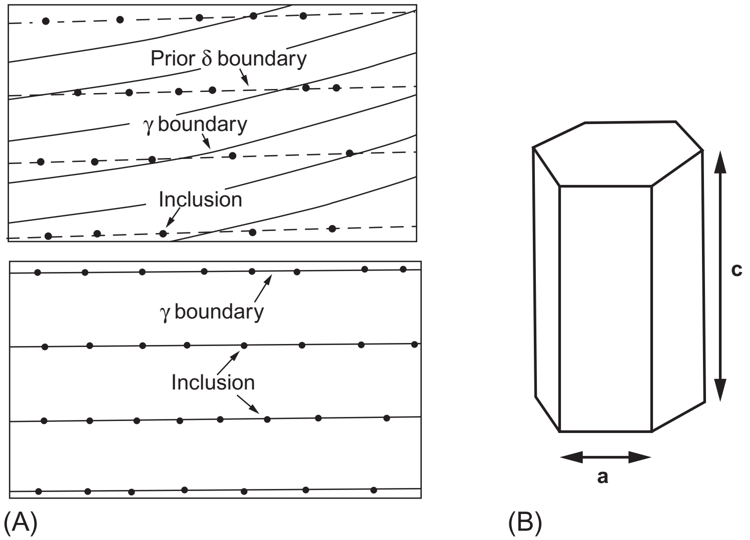


Figure 1-3-3 (A) Location of large inclusions for solidification as δ ferrite and as austenite. (B) A hexagonal prism model for the columnar austenite grains typical of the microstructure of steel weld metals.

of substitutional elements is in an order of magnitude larger in ferrite than in austenite. When this happens, any segregation is less likely to persist when liquid transforms to ferrite (Figure 1-3-3).

Crystal imperfections

Crystals are not always perfect; imperfections exist on the atomic scale, and such imperfections at the atomic level are called *vacancies*. Vacancies are empty atom sites. The lattice planes around a vacancy are distorted. Converse to the vacancies are the *interstitials*, which are an extra atom in the spaces of the lattice structure. Interstitials also produce lattice distortion.

Dislocations are disturbed regions between two substantially perfect parts of a crystal. Dislocations affect tensile and compressive properties of metal.

Grain size

Most engineering materials are polycrystalline. Grain boundaries are therefore an important feature of the microstructure. They can be manipulated to control the mechanical properties. For example, the strength σ increases as the grain size d is reduced. Hall-Petch has demonstrated this, and their equation supports the findings:

$$\sigma = \sigma_o + kd^{-1/2} \quad (\text{Hall} - \text{Petch equation})$$

In this relationship, the σ_o and k are functions of the atomic and microstructure, respectively. Grain size refinement is the only mechanism that simultaneously improves the strength and toughness, giving the metal its ability to absorb energy during fracture.

We have learned that the grain boundaries are defects that give an easy diffusion path. This implies that, at high temperatures, they would weaken the material by an easy diffusion of atoms in a way that leads to permanent creep. For elevated temperature applications, it is necessary to minimize the amount of grain boundary area per unit volume. This is the very reason that the turbine blades for jet engines are made of a single-crystal process, eliminating the formation of grain boundary and reducing the possibility of a weak phase.

The grain size can be controlled during the solidification stage by use of inoculants. A widely used alternative method is recrystallization.

The relation between the rate of growth and the rate of nucleation determines the size of grains in a casting. The cooling rate is the most important factor in determining grain size. Rapid cooling allows many nuclei to be formed resulting in a fine-grained material.

Insoluble impurities promote nucleation and promote fine grains. Disturbance of the melt during solidification tends to break up crystals before they become very large. In general, fine-grained materials exhibit better toughness and are harder and stronger than coarse-grained materials. Relatively coarse-grained material may be preferred for high-temperature service because there are fewer grain boundaries to provide high-temperature activation sites for deleterious reactions such as oxidation.

Low-temperature ductility and notch toughness of steel

The properties of various steel grades are dependent on their specific chemical compositions, processing, and the resulting microstructure; these properties are called *structure sensitive properties.*

Knowledge of these properties of steel is an essential part of correct selection and use of material to specific design conditions.

The microstructural constituents are known as ferrite, pearlite, cementite, bainite martensite, and austenite.

Most common structural steels produced are a mix of ferrite and pearlite. The carbon content and grain size determine the properties of this group of steel. For example, increasing the carbon content increases the tensile strength; however, with increasing carbon content, the ductility of steel also drops. Similarly, there is a corresponding relationship with the microstructure of steel to its toughness properties. Grain size percent of perlite and constituent elements play important roles in steels' toughness. Equations have been developed to assess the toughness of specific steel. F.B. Pickering developed a flowing equation in his 1971 publication, "*Towards Improved Toughness and Ductility*."

$$\mathrm{YS} = 53.9 + 32.34\,(\mathrm{Mn}) + 83.2\,(\mathrm{Si}) + 35.2\,(\mathrm{N_f}) + 17.4\mathrm{d}^{-0.5}$$

In this equation, the yield strength is determined by adding the percent of manganese, silicon, and free nitrogen with their reciprocals, and the diameter of the ferrite grain size. The presence of nitrogen in steel is often below 0.010%; however, its presence has a serious effect on reducing the impact properties of steel, which is a measure of steel's toughness. It is well known that absorbed energy of Charpy V-notch is reduced by increasing the carbon in steel. The carbon affects the percentage of pearlite in the steel microstructure. This effect is brought out through the regression equation for the transition temperature (TT) used by F.B. Pickering in his 1971 publication referenced earlier.

$$\mathrm{TT} = -19 + 44\,(\mathrm{Si}) + 700\left(\mathrm{N_f}^{0.5}\right) + 2.2\,(\mathrm{P}) - 11.5\left(\mathrm{d}^{-0.5}\right)$$

From this, we can deduce that, although ferrite grain size is helpful in improving both the strength and the toughness of steel, pearlite and nitrogen are not beneficial to improving the toughness properties.

This hypothesis has led to developments in the steelmaking process where control of grain size and microalloying, in fact, are both jointly practiced in production of steels with higher strength and better toughness.

The transition temperature of a metal, especially that of steel, is referred as the temperature—often a range of temperature—within which steel changes its ductility and becomes brittle. The change is often referred to as ductile to brittle transition, and the temperature at which this change occurs is called the specific steel's ductile to brittle transition temperature (DBTT). This is often determined by notch toughness testing of various types as discussed in the section describing various tests.

There are different ways to assess the DBTT; it can be either by assessing the 50-50 fracture appearance method or the lowest temperature at which the fracture is 100% ductile.

The term is also used to define the temperature range in which the ductility rapidly changes with the lowering of temperature.

The property of the material is important when the design is being done as the steel faces extremely low temperature either due to climatic conditions or due to process-related conditions.

The low-temperature ductility and notch toughness associated with fine grain steels is discussed in more detail in chapters dedicated to material testing and case studies on steel's transition temperature.

The concept of low-temperature ductility and transition temperature is also discussed in detail in the case study paper published in *Pipeline and Gas Journal*, June 2009, which is included as part of this book.

Selection Of Pipe Material For Low-Temperature Service

By **Ramesh Singh,**
Senior Principal Engineer,
Gulf Interstate Engineering,
Houston

The selection of material for any specific environment is directly dependent on the material's properties, especially those properties that are affected by that special environment. Metal properties are classified in terms of Mechanical, Physical and Chemical properties. These are further subdivided into Structure Sensitive or Structure Insensitive properties. The following table describes these properties.

Metal Properties ▼	Structure Insensitive Properties	Structure Sensitive Properties
Mechanical	Elastic-Moduli	Tensile strength, Yield Strength, Tensile elongation, True Breaking strength, Elastic Limit, Proportional Limit, Cree-Rupture Strength, Creep Strength, Strain Hardening Rate, Tensile Reduction of Area, Fracture Strength, Fatigue Strength, Impact Strength, Hardness, Damping Capacity,
Physical	Thermal expansion, Thermal conductivity, Melting point, Specific Heat, Emissivity, Vapor Pressure, Density, Thermal Evaporation, Thermoelectric, Properties, Thermionic emission.	Magnetic Properties, Electric Properties
Chemical	Electrochemical Potential, Oxidation Resistance, Catalytic Effects.	

Table 1: Metal properties.

In this article, we are concerned only with the structure-sensitive mechanical properties of metal. Metals are favored as a construction material because they offer a combination of mechanical properties that are unique and not found among non-metals. Metals are generally strong and many can be loaded or stressed to very high levels before breaking. One property of metals of interest is their capacity to exhibit a high degree of elastic behavior in their early load-carrying capacity. This is a very important property for effective use of the metal as a construction material. When these metals are loaded beyond their elastic range they exhibit another set of important properties called ductility and toughness. These properties and how they are affected by change in temperature are the point of this article.

Pipeline Steels

We will focus on carbon and low-alloy steels. It may be noted that the bulk of the material that is used in conventional pipeline engineering comes from this generic group. Aptly, it is the ductility and toughness of these metals and how they are affected by the variation of temperature that is our subject. The emphasis is made on the variation under low temperature. For this purpose it is essential to know what is meant by these metal properties and by low temperature. The following definitions are understood by fracture mechanics.

Ductility is defined as the amount of plastic deformation that metal undergoes in resisting the fracture under stress. This is a structure-sensitive property and is affected by the chemical composition.

Toughness is the ability of the metal to deform plastically and absorb energy in the process before fracturing. This mechanical and structure sensitive property is the indicator of how the given metal would fail at the application of stress beyond the capacity of the metal, and whether that failure will be ductile or brittle. Only one assessment of toughness can be made with some reasonable accuracy from ordinary tensile testing, and that is the metal displays either ductile or brittle behavior. From that it can be assumed that the metal displaying little ductility is unlikely to display a ductile failure if stressed beyond its limits. The failure in this case would be brittle.

The temperature of metal is found to have profound influence on the brittle/ductile behavior. The influence of higher temperature on metal behavior is considerable. The rise in temperature is often associated with increased ductility and corresponding lowering of the yield strength. The rupture at elevated temperatures is often intergranular, and little or no deformation of the fractured surface may have occurred. When lowered below room temperature, the propensity for brittle fracture increases.

ASTM E 616 defines some of the terminology associated with Fracture Mechanics and Testing, such as:

- The term fracture is strictly defined as irregular surface that forms when metal is broken into separate parts. If the fracture has propagated only part way in the metal and metal is still in one piece, it is called a crack.
- A crack is defined as two coincident-free surfaces in a metal that join along a common front called the crack tip, which is usually very sharp.
- The term fracture is used when the separation in metal occurs at relatively low temperature and metal ductility and toughness performance is the chief topic.
- The term rupture is more associated with the discussion of metal separation at elevated temperatures.

As noted previously, two basic types of fracture occur in metals: ductile and brittle. These two modes are easily recognized when they occur in exclusion, but fractures in metal often have mixed morphology and that is aptly called mixed mode. The mechanisms that initiate the fracture are shear fracture, cleavage fracture, and intergranular fracture. Only the shear mechanism produces ductile fracture. It may be noted that like the modes discussed here, the failure mechanisms also have no exclusivity.

A crack is defined above as two coincident-free surfaces in a metal that join along a common front called the crack tip, which is usually very sharp. Irrespective of the fracture being ductile or brittle, the fracture process is viewed as having two principal steps:

1. Crack initiation, and
2. Crack propagation.

Knowledge of these two steps is essential as there is a noticeable difference in the amount of energy required to execute them. The relative level of energy required for initiation and for propagation determines the course of events which will occur when the metal is subjected to stress.

There are several aspects to the fracture mechanics that tie in with the subject of metal ductility and toughness but this article is not planned for detailed information on fracture mechanics. Hence, these are not discussed in detail but some specific-related topics are listed in Table 2.

Table 2: Topics related to fracture mechanics.
- Effects of axiality of stress,
- Crack arrest theory,
- Stress intensity representation,
- Stress gradient,
- Rate of Strain,
- Effect of Cyclic Stress,
- Fatigue Crack,
- Crack Propagation, ($K_{Ic} = \sigma \sqrt{\pi a}$)
- Griffith's theory of fracture mechanics,
- Irwin's $K = \sqrt{E \times G}$,
- Crack Surface Displacement Mode,
- Crack Tip Opening Displacement (CTOD), (BS 5762-1979 and BS 7448 part-I)
- R-Curve Test methods
- J- Integral Test method,
- Linear-Elastic Fracture Mechanics (LEFM) (ASTM E 399),
- Elastic-Plastic Fracture Mechanics (EPFM),
- Nil Ductility Temperature (NDT).

Though the topics in Table 2 are not commonly taken into consideration when selecting suitable material for an onshore pipeline, these are essential parts of subsea pipeline and riser technology. In fact, some of the specification (e.g. API 1104, DNV-OS F101 etc.) suggest the use of fracture mechanics to determine the failure behavior of metal in these services.

Returning to our earlier discussion, lowering the temperature of metal profoundly affects fracture behavior. Strength, ductility, toughness and other properties are changed in all metals when they are exposed to temperature near absolute zero. The properties of metals at very low temperatures are of more than casual interest because pipelines, welded pressure equipment and vessels are expected to operate satisfactorily at levels below room temperatures. For example, moderate sub-zero temperatures are imposed on equipment for dewaxing petroleum and for storage of nitrogen, liquefied fuel gases and pipelines.

Much lower temperatures are involved in cryogenic services where metal temperature falls to –100°C (-150°F) and below. The cryogenic service may involve storage of liquefied industrial gases like oxygen and nitrogen. Toward the very bottom of the temperature scale, there is a real challenge for metals that are used in the construction of equipment for producing and containing liquid hydrogen and liquid helium,because these elements in liquefied form are increasingly important in new technologies. Helium in liquefied form is only slightly above absolute zero, which is 1 Kelvin (-273.16°C or – 459.69°F).

Absolute zero (1°K) is the theoretical temperature at which matter has no kinetic energy and atoms no longer exhibit motion. Man has yet to cool any material to absolute zero, so it is unknown how metals would behave when cooled to this boundary condition.

However, metal components have been brought to the temperatures very close to absolute zero, hence it presents a special challenge to metals and welded components as they would be required to serve in this extremely low temperature.

When cooled below room temperature every metal will reach a temperature where the kinetic energy will be reduced to nil. The atoms of the element will move closer and the lattice parameters will become smaller. All these changes would affect the mechanical properties of the metal.

Metal Strength At Low Temperature

As we have seen, as temperature is lowered from room temperature, 75°F (24°C or 297°K), to absolute zero, 1°K, the atoms of an element move closer together by dimensions easily compounded from the coefficient of thermal expansion. Several changes occur as a result of this smaller lattice parameter. For example, the elastic module increases. In general, the tensile strength and yield strength of all materials increase as the temperature is lowered to the nil ductility temperature (NDT) , where the yield and tensile strength are equal ($\pi_o = \pi_u$). The change in these properties is variable in degree for different metals but change does occur.

When the temperature of low-carbon or low-alloy steel is lowered, the corresponding increase in strength of metals occurs. This is attributed to an increase in resistance to plastic flow. Because

plastic flow is strongly dependent upon the nature of the crystalline structure, it would be logical to assume that metals with the same kind of structure would react similarly.

A cautionary note: The material in ASTM A 333 Grades 1,3,4,6,9 and 10 is required to have minimum of 10 ft-lbs absorbed energy (impact values).This is the same as ASTM A 350 LF1, but material ASTM A 350 LF2 and LF3 are required to have minimum of 12 ft-lbs absorbed energy (impact values). This is at any given temperature, respective of that material.

Selecting Material From Specification And Codebooks

There are several ASME/ASTM specifications specifically tailored for low-temperature services, but it is important to check if the specified test temperatures for the metal in use is in tally with the design temperature of the system. ASTM-A/ASME -SA105 is not a low-temperature material; however, it may be used for low temperature if all the other factors are conforming to the requirements and an additional impact test on the material is carried out at a temperature that is in tally with the design temperature.

Similarly, ASTM A 106 pipes (grade A, B or C) must be checked for the test temperatures because ASTM A 106 is specified as “high-temperature” material and rightfully the impact test is not even included in the non-mandatory requirement. The same is the case with ASTM A 105 forged material discussed above. Concerning ASTM A 333 grades 1, 3, 4, 6, 9 and 10 pipes for the acceptable impact values and their test temperatures, the specification must be referenced before arbitrarily using them for any service temperature range. ASTM A 350 LF1 (-20°F), LF2 (-50°F), LF 3 (-150 °F) are suitable for low-temperature service to the limits set by the specification, but one should check the specified energy absorption value Cv to ensure it is in tally with the system design parameters.

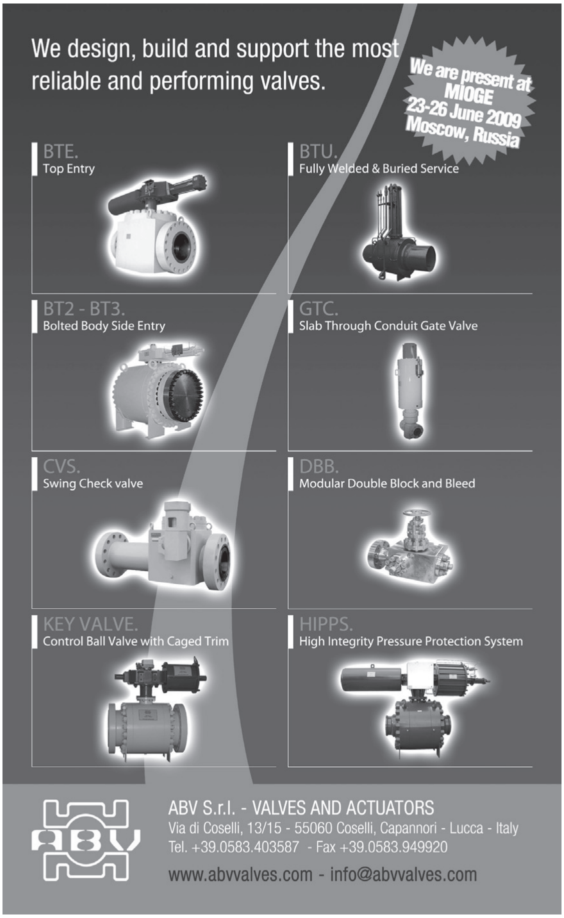
An informed selection has to be made. There are several boiler-quality plate materials specified by the ASTM specifications and ASME codes but not all are suitable for low-temperature services. Some are so designed metallurgically that they are not suitable for low-temperature service. Plate material conforming to the ASTM A 515 specification is an example. Most of the metals that are fit for low temperature are generally tested to 32°F (0°C) unless specified otherwise. So, the general assumption that all ASME material is good up to -20°F will not be correct, unless it is tested and material test report so declares.

API mandates that PSL2 pipes be tested at 32°F (0°C) or any lower temperature as agreed between the buyer and manufacturer and is expected to have 20 ft-lbs (27 J) absorbed energy. The same is not true for PSL1 pipes. In either case, it is important to determine what was the actual test temperature and what responsibility engineers have to ensure that the test temperature is in tally with the design temperature of the system.

Among pipeliners, a question is often raised if, in designing a buried pipeline, one needs to consider the low temperature. The answer is not metallurgical since it is unrelated to the material property as much as it is geographical and environmental, that is, the design conditions. The data provided by the user (clients) and the specification must be consulted.

Generally, a buried pipeline will not be subject to very low temperatures unless buried in permafrost, so no specific caution beyond the general design considerations would be required. However, the general guidance in such case should be to look at the product properties, risk analysis, product leakage, and will a reduction in pressure at a certain point reduce the temperature to what is considered a low-temperature range.

If there is a cause to expect lower temperature, then determine to what extent lower temperature will occur during the life of service. If the temperature is ever in the critical low range, it will be prudent to identify those conditions and take them into account while selecting the material.



Similar consideration applies to the aboveground pipe and components. Aboveground valves flanges and pipes are more exposed to the weather and are also carrying the similar product. Therefore, they have greater propensity to face low temperature in their service lives. The following questions must be asked and answered: Are they insulated? Are they heated? Is there any possibility of depressurization that would lead to extensive temperature reduction, etc? There is a multiplicity of factors that affect the understanding of the material behavior in extreme stress conditions. All possible factors must be identified and addressed.

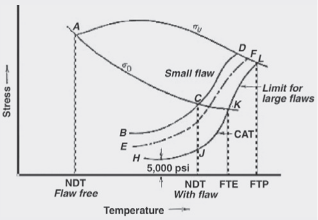
Conclusion

The questions we have tried to explore are more complex than this discussion which is an attempt to simplify the basic understanding of the subject. This discussion is intended to bring out the importance of the subject and direct readers to available resources for material selection issues. ***P&GJ***

Author: Ramesh Singh is a senior principal engineer for Gulf Interstate Engineering, 16010 Barkers Point Lane, Houston, TX 77079. He specializes in materials, welding and corrosion. He graduated from California Coast University with a master of science degree (2003) in engineering management and gained his basic metallurgical education (1984) from Air Force Technical Institute in

Important Additional Information

The sub-ambient temperature dependence of yield strength σ_o ($R_{p0.2}$) and ultimate tensile strength σ_u in a bcc metal is shown in Figure 1. Consider the graph, the material is ductile until a very low temperature, point A, where Y.S. equals the UTS of the material ($\sigma_o = \sigma_u$). Point A represents the NDT temperature for a flaw-free material. The curve BCD represents the fracture strength of a specimen containing a small flaw (a < 0.1mm). The temperature corresponding to point C is the highest temperature at which the fracture strength $\sigma_f \approx \sigma_o$. Thus point C represents the NDT for a specimen with a small flaw.



The presence of a small flaw raises the NDT of steel by about 200°F (110°C). Increasing the flaw size decreases the fracture stress curve, as in curve EF, until with increasing flaw size a limiting curve of fracture stress HJKL is reached. Below the NDT the limiting safe stress is 5,000-8,000 psi (~35 to 55 MPa).

Above the NDT the stress required for the unstable propagation of a long flaw (JKL) rises sharply with increasing temperature. This is the crack-arrest temperature curve (CAT). The CAT curve defines the highest temperature at which unstable crack propagation can occur at any stress level. Fracture will not occur for any point to the right of the CAT curve.

The temperature above which elastic stresses cannot propagate a crack is the fracture transition elastic (FTE). The temperature defines the FTE, at the point K, when the CAT curve crosses the Yield Strength, σ_o curve. The fracture transition plastic (FTP) is the temperature where the CAT curve crosses the Ultimate Tensile Strength σu curve (point L). Above this temperature, the material behaves as if it is flaw-free, for any crack, no matter how large, cannot propagate as an unstable fracture. ■

Structure of materials

4

The importance of grain size and phases of material is introduced in the previous chapter, where we noted that the properties of a material depend to a large extent on the type, number, amount, and form of the phases present, and altering these quantities can change these properties. In this chapter, we will discuss phase diagrams that explain the conditions under which phase exists and the conditions under which phase changes can occur. The term *phase* refers to the region of space occupied by a physically homogeneous material. Another term associated with physical homogenous material is *equilibrium*. We need to understand what is meant by the term equilibrium.

Equilibrium is defined as the dynamic condition of physical, chemical, mechanical, or atomic balance that appears to be in a condition of rest as compared with change.

Three variables are used to describe the state of a system in equilibrium:

(1) Temperature
(2) Pressure
(3) Composition

A phase diagram is a graphical representation of the temperature and composition limits of phase fields in an alloy. It may be in equilibrium or in a metastable condition.

There are three types of equilibria: stable, metastable, and unstable.

Stable equilibria exist when the material is in its least energy condition. Metastable equilibria are possible only when external energy has to be introduced to stabilize the material. The unstable state of equilibria is the state in which external energy is required to bring the material to either a metastable or stable state.

Phase diagrams assume a constant (ambient) pressure. Because equilibrium conditions do not normally exist during heating and cooling, phase changes tend to actually occur at temperatures slightly higher or lower than the phase diagram would indicate. Rapid variations in temperature can prevent normally occurring phase changes.

Phase diagrams

Phase diagrams, also called equilibrium diagrams or constitutional diagrams, are usually plotted with temperature at the ordinate and alloy composition in weight percentage at the abscissa. Phase diagrams are useful in efficient and cost-effective understanding of alloys in various stages of research, development, and production. For example, they are useful in various aspects of metallurgical studies, such as the development of new alloys, fabrication of these alloys, heat treatment procedures for developing specific properties, and resolution of issues arising from application of specific alloys.

The term "phase" was first used by J. William Gibbs who laid down the following rule called the "Phase rule" to describe the relationship of temperature, pressure, and

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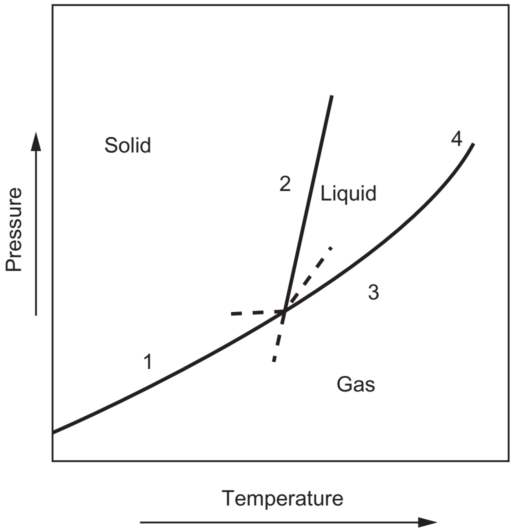
Figure 1-4-1 Pressure temperature phase diagram.



number of homogeneous regions (phase) and number of components. The rule can be described as:

$$f = c - p + 2 \qquad [1]$$

where,

f is the number of independent variables called degree of freedom,
c is the number of components, and
p is the number of stable phases in the system.

Different types of phase diagrams

Phase diagrams can depict the changes at various temperatures and/or pressures, involving one or several components, as depicted in Figure 1-4-1. They are annotated with Latin letters.

Unary diagram is of one component; it is a simple two-dimensional depiction of phase changes as temperature and/or pressure changes. The phase rule states that all three can exist in stable equilibrium only at a single point on a unary diagram ($f = 1 - 3 + 2 = 0$). In this diagram, the three phases of solid, liquid, and gas coexist, and the equilibrium occurs at the interface of the two adjoining phases. The invariant equilibrium among all three phases occurs at the point called *triple point* where the three phases intersect. This point is called *invariant* because, at this point, all external variables are fixed; in other words, there is no degree of freedom $f = 0$. The variation in either temperature or pressure can change the equilibrium, and one or two of the phases may disappear.

Contrasted with invariant equilibrium discussed earlier are the uninvariant and bivariant equilibriums.

Uninvariant equilibrium or monovariant is about two phases in a unary system that allows one degree of freedom ($f = 1 - 2 + 2 = 1$).

Bivariant equilibrium allows for both the temperature and pressure to be arbitrarily selected. This allows for two degrees of freedom.

Binary diagram is of two components. In this system diagram, a third dimension is also added to the graph. Because most metallurgical problems study under one atmosphere, the graph is reduced to a two-dimensional plot of temperature and composition. Because the pressure is held constant, the phase rule changes.

$$f = \mathrm{c} - \mathrm{p} + 1 \qquad [2]$$

For a binary system with two components, the stable equilibria could be one of the following:

With one phase, the degree of separation will be two.
With two phases, the degree of separation will be one.
With three phases, the degree of separation will be zero.

In a binary system, if the two components have the same crystal structure, then usually the two metals would have the same kind of crystal structure and also similar atomic radii, therefore they are completely soluble in each other. These are also called *miscible solids*. The only type of solid phase formed will be a substitutional solid solution. In such a diagram, the boundary between the liquid field and the two-phase field is called *liquidus* and the space between the two-phase fields and solid field is called *solidus*. A series of cooling curves for various compositions is obtained by experiment, and they are combined to form the phase diagram.

The upper line connecting the points showing the beginning of solidification is the liquidus line. The area above the liquidus line is a single-phase region of a homogeneous liquid solution. The lower line connecting the points showing the end of solidification is the solidus line. The area below is a single-phase region of a homogeneous solid solution (Figure 1-4-2).

The liquidus is the locus in a phase diagram, and it represents the temperature at which the alloy system begins to freeze on cooling or finishes melting on heating. The solidus is the locus in a phase diagram, and it represents the temperature at which the alloy finishes freezing on cooling or begins melting on heating. When the phase is in an equilibrium field, it is called *conjugated phase*. When the liquidus and solidus tangentially meet at some point, a maximum and minimum are produced in the phase fields.

Ternary phase diagram, as the name suggests, is the diagram that addresses the alloys consisting of three components. The phase diagram of such an alloy is plotted within a triangle. Figure 1-4-3 is a ternary phase diagram.

Each side of the triangle functions as the composition abscissa for a binary system, AB, BC, and CA. The composition for the given alloy at point X on the diagram is 20% A, 40% B, and 40% C. To indicate the role of temperature and phase present

Figure 1-4-2 Binary diagram of a eutectoid system.

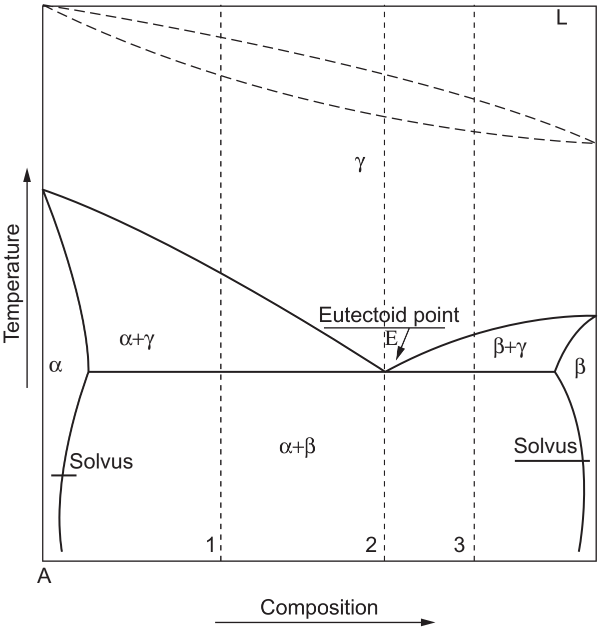
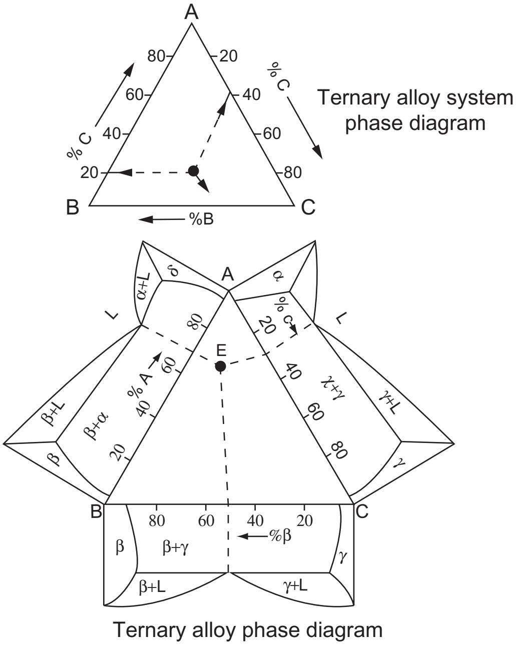


Figure 1-4-3 Ternary diagrams.



Ternary alloy phase diagram
Lowest-melting eutectic composition point is E.

at a given temperature level on the ternary diagram, it is necessary to move onto the third dimension. This can be done in several different ways; diagrammatically, a binary phase diagram can be drawn from each of the abscissa on the sides of triangle as shown in figure for a eutectic alloy system. A ternary system does not facilitate designation of temperature limits for phase fields. It is however possible to construct several binary phase diagrams to indicate the contents of one or the other components at the fixed points.

The other phase diagrams are shown in the following list. They are not part of the discussion, hence their details are not discussed in this book.

- Quaternary diagram is of four components.
- Quinary diagram is of five components.
- Sexinary diagram is of six components.
- Septenary diagram is of seven components.
- Octanary diagram is of eight components.
- Nonary diagram is of nine components.
- Decinary diagram is of 10 components.

Iron-iron carbide phase diagram

Our discussion of the phase diagram would be incomplete without discussing the most used and referenced phase diagram of industrial application, the iron-iron carbide phase diagram.

A great verity of changes is possible in iron by alloying with carbon. These possibilities are commercially exploited by developing new and varied grades of steels with equally varied properties. Carbon is an element with atomic weight of 12 that exists in three allotropic forms. The first is amorphous carbon in the form of lampblack and coal, etc. The second form is graphite, and the third form is diamond. The melting point of carbon varies, but it is somewhere close to 3300°C (6000°F). This clearly indicates that carbon is present in iron in a solid state, and in molten iron, it forms solutions. The state of carbon in solid iron is very complex and varied. Carbon is an austenite former, because it extends the temperature range over which the fcc crystalline structure is stable. A good amount of carbon is dissolved in gamma (γ)-iron (fcc) and forms intermetallic solution. The solubility of carbon in alpha (α)-iron (bcc) is very limited. A maximum of 0.0218% can be retained at 727°C (1340°F) in interstitial solution, but its solubility at room temperature drops to 0.008%. The carbon that cannot remain in solid solution in alpha-iron or ferrite will form a compound for the most part rather than exist in free form of carbon; this compound is iron-carbide (Fe_3C) also called “cementite.” This is the reason the phase diagram of iron and carbon is called an iron-iron carbide diagram.

Carbon can exist in iron alloys as free carbon in the form of graphite, but this form is found with very high carbon content, such as gray cast iron, which is discussed in subsequent chapters.

Explanation of iron-carbon phase diagram

In Figure 1-4-4, the composition at abscissa (horizontal direction) and temperature on ordinate (vertical direction) are correlated at atmospheric pressure. The weight percentage of components on the abscissa is plotted on a logarithmic scale, to allow for expansion of areas of interest in carbon percentages in lower range and to compress the area of cast iron, which is of relative lower interest. The atomic percentage is indicated on the top horizontal line. Both Celsius and Fahrenheit temperature scales are used for proper understanding of the phase diagram.

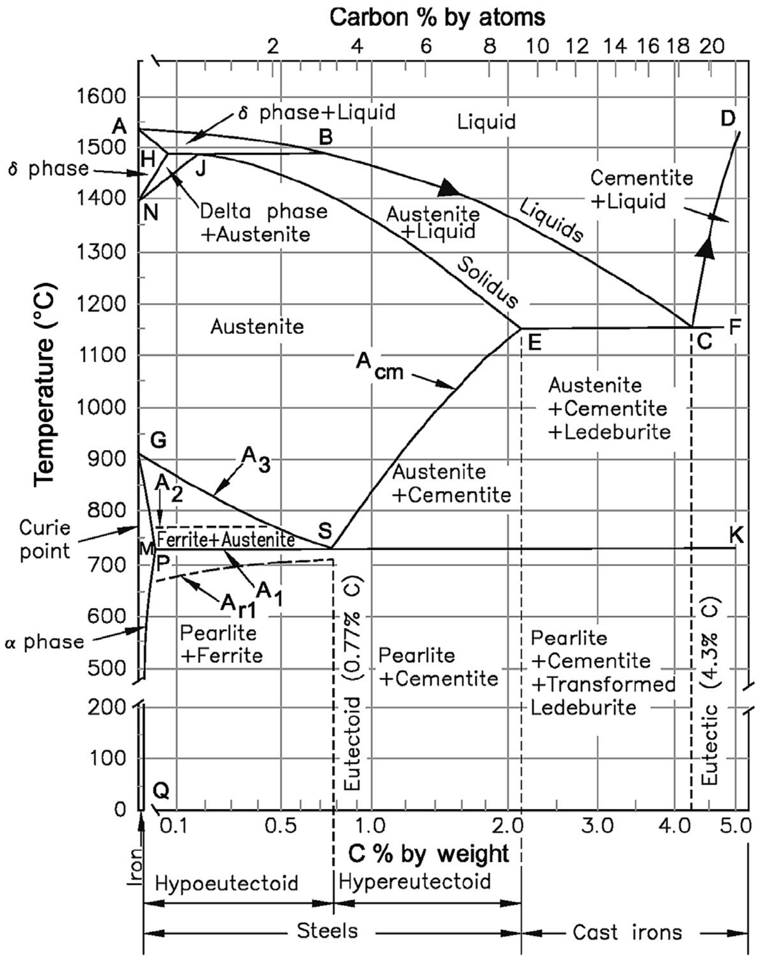


Figure 1-4-4 Iron-carbon phase diagram.

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The iron-iron carbide alloy has a eutectic and a peritectic reaction; the addition of carbon lowers the freezing temperature of alloys containing up to about 5% carbon and causes solidification over a range of temperature, which, as discussed earlier, is the typical effect of alloying.

As carbon is added, the liquidus steadily decreases along curve ABC until a eutectic composition is reached at about 4.3% carbon. Further increase in carbon content causes the liquidus to rise along the CD curve. In general, the liquidus of steels is lowered over a relatively small temperature range as carbon content is increased up to the maximum incorporated in high-carbon steels. Cast irons however have a substantially lower liquidus as compared with steels. This difference is clearly noted when welding the two materials.

Most steels that are subject to welding usually contain up to maximum 0.5% carbon, so there is reason to give closer attention to this section of the phase diagram. In a steel-melt containing less than 0.53% carbon, the first crystals of solidification to appear below the liquidus AB are δ (bcc) phase. The composition indicated by line AH is part of the solidus AHJEF curve. The terms delta-iron and delta-ferrite are used to designate either iron that is free of carbon, or a solid solution of iron and carbon that has the bcc crystalline structure just below its solidus at temperature level of 1495°C (2723°F). The alloys with carbon content between 0.09% to 0.53% encounter peritectic boundaries. With carbon content above 0.53%, the crystals that form as the temperature reaches the liquidus BC are called *austenite*. This phase is an interstitial solid solution of carbon in γ-iron (fcc).

The line JE shows the composition of this primary austenite crystal. Austenite formed as δ phase along line HN during cooling is called *secondary austenite*. A summation of important phases that are formed during solidification are listed here.

H	Delta (δ) phase (bcc) containing 0.09% carbon.
J	Gamma (γ) phase (fcc) containing 0.17% carbon (Peritectic composition).
B	Peritectic liquid, containing 0.53% carbon.
HJB	Peritectic temperature 1495°C (2723°F).
NJE	Austenite (γ) phase (fcc) with carbon in interstitial solid solution.

Because the outcome of the reaction is not shown in the final microstructure of carbon and low alloy steels, little attention is paid to the peritectic reaction in solidification stages. In high alloys, however, the peritectic reaction assumes importance because the reaction often does not proceed to completion, and small amounts of δ phase (bcc) of a different structure may be retained in a matrix.

During cooling below the liquidus BC, the iron-carbon composition that contains 2% and up to 4.3% carbon is first to form austenite. The carbon content of the austenite can be ascertained by applying the lever law to the solidus JE. This primary solid will be lower in carbon than the overall alloy composition, and when the temperature reaches the eutectic line EC, the remaining liquid will be enriched to the eutectic carbon content of 4.3%. At final solidification at 1154°C (2109°F), the eutectic line on the diagram proceeds by formation of a eutectic consisting of metastable austenite and cementite. This structure is also called *ledeburite*. On continued cooling below the eutectic boundary PSK at 727°C (1341°F), the metastable austenite undergoes a eutectoid reaction and decomposes into ferrite and cementite, a structure known as *pearlite*.

In compositions containing over 4.3% carbon, the first crystals appear when temperature reaches liquidus CD line during cooling crystals of cementite in iron-carbon compound Fe_3C, which contains 6.67% carbon. Following is a brief summary of the diagram.

ECF part of the eutectic line, which extends to 6.67% carbon (outer limit 6.67% carbon is outside the diagram).

E	Eutectic austenite, 2.1% carbon
C	Eutectic liquid, 4.3% carbon

Along line ECF, the three components austenite, eutectic liquid (E), and cementite (C) are in equilibrium. If heat is applied, austenite E and cementite react to form a liquid containing 4.3% carbon at constant temperature of 1145°C (2109°F). If heat is removed, the eutectic liquid C discharges austenite E and cementite is finally divided into eutectic form. Liquid is not found below the solidus AHJEF.

Besides the not-so-significant lines NJ and NH that encompass delta phase austenite, there are only five lines in the phase that are below the solidus. We shall discuss the two remaining points P and S.

Lines GS and SE are analogous to lines AC and CD; molten alloy-liquid solution is analogous to austenite-solid solution. When solid solution of austenite reaches GS (Ar_3) on cooling, crystals of alpha-iron appear and the composition is called *ferrite*. Without cementite and austenite support, ferrite can exist only in the area left of GPQ. When austenite reaches SE (A_{cm}) on cooling, crystals of cementite start to appear. Pertinent details of the eutectoid portion of the phase diagram are given here.

PSK	Part of the eutectoid line 727°C (1341°F)
P	Eutectoid ferrite, containing 0.0218% carbon
S	The eutectoid, containing 0.77% carbon

The right end of the eutectoid line extends to 6.67% carbon, corresponding to the composition of cementite, Fe_3C. Along the line PSK, the material P, S, and cementite are in equilibrium. If heat is applied, P and cementite react to form austenite of composition S, containing 0.77% carbon, at temperature 727°C (1341°F). If, however, the heat is removed, then S decomposes into ferrite (P) and cementite. The crystals of ferrite and cementite arrange themselves in a lamellar structure with a thin plate of cementite separating every pair of ferrite plates. This structure is called *pearlite*.

The transformation temperatures identified as A_1 and A_3 for iron-carbon alloys can vary from those shown by boundary drawn in the graph. If either the heating or cooling rate is faster than the very slow rate required to establish the equilibrium conditions, the transformation will occur at somewhat different temperatures.

Rationale for letter designations in iron-iron carbide phase diagram

Two of the alphabetical designations in Figure 1-4-4 deserve further explanation.

- M designation, which marks the change in magnetic properties of iron at 770°C (1418°F), is the Curie point.
- A_2 designation indicates this same change in steel.

The importance of critical temperatures in dealing with steels has fostered the practice of marking not only the occurrence of these changes in the solid state but also their sequence and conditions under which the specific temperature point was determined. These critical temperatures are determined by plotting a curve, and the letter A is employed. Etymologically, the letter A comes from the French word *arrêt* meaning arrest. The transformation in the solid state can involve diffusion and thereby requires more time than in the liquid state. Hence, it is important to indicate the conditions at which the temperature was recorded.

When a phase change is determined during a slow rate of heating, the critical temperature would be labeled A_c. (The letter c coming from French word *chauffage* meaning heating.) If the determination was made during slow cooling, the designation will be A_r. (The letter r coming from another French word *refroidissement* meaning cooling.) When critical temperature for phase transformation is established under equilibrium conditions, the designation is A_e. (The letter e is for equilibrium.)

The sequence of phase transformation in steel is viewed from their occurrence during heating, therefore the lowest critical point is marked as A_{C1}, and the subsequent points are A_{C2} and $A_{C3.}$ The notation A_{cm} is used to designate the curve, and this indicates the start of austenite transformation in hypereutectoid steel that has a carbon percentage >0.77% during cooling where cementite forms.

Production of steel

5

With a basic understanding of physical metallurgy, behavior of iron and steel on heating and cooling, and the process of solidification and phase formation, now is an appropriate time to study the steel-making process.

Steelmaking is an ancient process, and several developments have occurred in the technology over the period.

Two processes commonly used for production of steel are the basic oxygen furnace (BOF) and the electric arc furnace (EAF), and each uses a variety of charge materials and technologies.

The EAF process uses virtually 100% old steel to make new steel. EAFs make up approximately 60% of today's steelmaking in the United States. The operational details of EAF and BOF processes are discussed in the following.

Electric arc furnace (EAF) process

As the name implies, the process uses an EAF to melt the charge to make steel. It is a batch melting process producing batches of molten steel known as *heats*. The EAF operating cycle is called the tap-to-tap cycle and is made up of the following operations:

1. Furnace charging
2. Melting
3. Refining
4. Deslaging
5. Tapping
6. Furnace turn around

The tap-to-tap cycle time is generally less than 60 min; some double-shell furnace operations are able to reduce the tap-to-tap time to about 30–40 min.

Furnace charging

The first step in the production of any heat is to select the grade of steel to be made. Usually a schedule is developed prior to each production shift. Thus the melter will know in advance the schedule for his shift. The scrapyard operator will prepare buckets of scrap according to the needs of the melter. Preparation of the charge bucket is an important operation, not only to ensure proper melt-in chemistry but also to ensure good melting conditions. The scrap must be layered in the bucket according to size and density to promote the rapid formation of a liquid pool of steel in the hearth

Applied Welding Engineering. https://doi.org/10.1016/B978-0-12-821348-3.00006-9

while providing protection for the sidewalls and roof from electric arc radiation. Other considerations include the following points:

- Minimization of scrap cave-ins, which can break electrodes
- Ensuring that large heavy pieces of scrap do not lie directly in front of burner ports, which would result in blowback of the flame onto the water-cooled panels

Generally, a charge would include lime and carbon but these can be injected later during the furnace operation. Often mills practice a combination of both.

The first step in any tap-to-tap cycle is "charging" the scrap. The roof and electrodes of the furnace are raised and swung aside to allow the scrap-charging crane to place a fully loaded scrap bucket over the top of the furnace opening. The bucket's bottom operates like a clamshell, and it opens up by retracting two segments on the bottom of the bucket letting the scrap fall into the furnace. The roof and electrodes then swing back into place over the furnace. The roof and electrodes are lowered to strike an arc on the scrap. This commences the melting portion of the cycle. The number of charge buckets of scrap required to produce a heat of steel primarily depends on the capacity volume of the furnace and the scrap density.

Modern furnaces are designed to operate with a minimum of back-charges. This is advantageous because charging time is dead time for a furnace. Reducing dead times allows for increased production time of the furnace and reduction in loss of energy. Dead time of a furnace can amount to about 10–20 kWh/ton for each occurrence. Generally about two or three buckets of scrap are charged for each heat.

Melting

The EAF process has developed as an efficient melting apparatus. The modern designs focus on increased capacity of the furnace. Melting is accomplished by supply of energy to the furnace interior. This energy can be electrical or chemical. Electrical energy is supplied via the graphite electrodes and is usually the largest contributor in melting operations. Initially, an intermediate voltage tap is selected until the electrodes dig into the scrap. Usually, light scrap is placed on top of the charge to accelerate bore-in. About 15% of the scrap is melted during the initial bore-in period. After a few minutes, the electrodes penetrate the scrap deep enough to allow for a high voltage tap that would develop long arc without fear of radiation damage to the roof. The long arc maximizes the heat of the arc, as it transfers the power to the scrap and a liquid pool of metal in the hearth of the furnace.

The initiation of arc creates an erratic and unstable arc, and wide swings in current are observed accompanied by rapid movement of the electrodes. As the temperature in the furnace rises, the arc stabilizes. As the molten pool is formed, the arc becomes quite stable and the average power input increases.

Chemical energy is supplied via several sources including oxy-fuel burners and oxygen lances. Oxy-fuel burners burn natural gas using oxygen or a blend of oxygen and air. Heat is transferred to the scrap by flame radiation and convection by the hot products of combustion. Heat is transferred within the scrap by conduction. Large pieces of scrap take longer to melt into the bath than smaller pieces. In some operations, oxygen is injected via a consumable pipe lance to "cut" the scrap. The oxygen reacts with the hot scrap and burns iron to produce intense heat for cutting the scrap. Once a molten pool of steel is generated, oxygen can be lanced directly into the molten bath of steel. The oxygen reacts with several components in the bath including aluminum, silicon, manganese, phosphorus, carbon, and iron. All of these reactions are exothermic and supply additional energy to aid in the melting of the scrap. The metallic oxides that are formed end up in the slag. The reaction of oxygen with carbon in the bath produces carbon monoxide, which either burns in the furnace if there is sufficient oxygen, and/or is exhausted through the direct evacuation system where it is burned and conveyed to the pollution control system.

Once enough scrap has been melted to accommodate the second charge, the charging process is repeated. Once the final scrap charge is melted, the furnace sidewalls are exposed to intense radiation from the arc. As a result, the voltage is reduced. Alternatively, creation of a foamy slag allows the arc to be buried. This protects the furnace shell. In addition, a greater amount of energy is retained in the slag and is transferred to the bath resulting in greater energy efficiency.

Once the final scrap charge is fully melted, flat bath conditions are reached. At this point, bath temperature is taken and a sample is collected. The analysis of the bath chemistry allows the melter to determine the amount of oxygen to be blown during refining. At this point, the melter can also start to arrange for the bulk tap alloy additions to be made. These quantities are finalized after the refining period.

Refining

Traditionally the refining operations in the EAF involves the removal of phosphorus, sulfur, aluminum, silicon, manganese, and carbon from the steel. However new developments in understanding the role of dissolved gases, especially hydrogen and nitrogen, make it essential that these gases are also removed to acceptable limits. These gases are not removed during the refining operations once a flat bath is achieved. The presence of oxygen in the bath during the flat bath operation reduces the carbon content to the desired level for tapping. Most of the compounds to be removed during refining have a higher affinity for oxygen than carbon. Thus the oxygen reacts preferentially with these elements to form oxides, as they float out of the steel and through the slag.

In modern EAF operations, especially those operating with a "hot heel" of molten steel and slag retained from the prior heat, oxygen is often blown into the bath throughout the heat. This technique allows for the simultaneous operation of melting and refining in the furnace.

Phosphorus removal

Higher concentrations of phosphorus and sulfur are normally present in the furnace charge and must be removed to acceptable limits. Unfortunately the conditions favorable for removing phosphorus are the opposite of those for the removal of sulfur.

Therefore once these materials are pushed into the slag phase, they can revert back into the steel. Phosphorus retention in the slag is a function of the following factors:

1. Bath temperature
2. The slag basicity
3. FeO levels in the slag

At higher temperature or low FeO levels, the phosphorus reverts from the slag back into the bath. Phosphorus removal is carried out as early as possible in the heat. Hot heel practice is very beneficial in phosphorus removal because oxygen can be lanced into the bath while its temperature is quite low. Early in the heat, the slag contains high levels of FeO as it is carried over from the previous heat, which helps removal of phosphorus. High slag basicity (i.e., high lime content) is also beneficial for phosphorus removal. This method has some limitations, as saturation of slag with lime increases the viscosity of slag, making it less effective. To increase the fluidity of slag (fluidizing the slag), fluorspar is added. Stirring the bath with inert gas is also beneficial because it renews the slag-to-metal interface thus improving the reaction kinetics.

In general, if low phosphorus levels are the requirement for a particular steel grade, the scrap is selected to give a low level at melt-in, and usually the phosphorus is reduced by 20%–50% in the EAF process.

Sulfur removal

Sulfur is removed mainly as a sulfide dissolved in the slag. The sulfur partition between the slag and metal is dependent on slag chemistry and is favored at low steel oxidation levels. Removal of sulfur in the EAF is difficult especially in modern practices where the oxidation level of the bath is high. Generally the partition ratio is between 3 and 5 for EAF operations. Most operations find it more effective to desulfurize during the reduction phase of steelmaking. This means that desulphurization is performed during tapping (where a calcium aluminate slag is built) and during ladle furnace operations. For reducing conditions where the bath has a much lower oxygen activity, distribution ratios for sulfur of between 20 and 100 can be achieved.

Control of the metallic constituents in the bath determines the properties of the final product. Usually, the melter aims at lower levels in the bath than are specified for the final product. Oxygen reacts with aluminum, silicon, and manganese to form metallic oxides, which are slag components. These metallic oxides tend to react with oxygen before the carbon. They also react with FeO resulting in a recovery of iron units to the bath. For example:

$$\mathrm{Mn} + \mathrm{FeO} = \mathrm{MnO} + \mathrm{Fe}$$

Manganese is typically lowered to about 0.06% in the bath.

The reaction of carbon with oxygen in the bath to produce carbon monoxide (CO) is an important step, as it supplies a less expensive form of energy to the bath and performs several important refining reactions. In modern EAF operations, the combination of oxygen with carbon can supply between 30% and 40% of net heat input to the furnace. Evolution of carbon monoxide is very important for slag foaming. Coupled with a basic slag, CO bubbles are tapped in the slag causing it to "foam" and helping to bury the arc. This greatly improves thermal efficiency and allows the furnace to operate at high arc voltages even after a flat bath has been achieved. Burying the arc also helps to prevent nitrogen from being exposed to the arc where it can dissociate and enter the steel.

Nitrogen and hydrogen control

If the CO gas is evolved within the steel bath, it helps to strip nitrogen and hydrogen from the steel. At 1600°C, the maximum solubility of nitrogen in pure iron is 450 ppm. Typically, the nitrogen levels in the steel following tapping are 80–100 ppm. Nitrogen levels in steel as low as 50 ppm are achieved in the furnace prior to tapping. Bottom tapping is beneficial for maintaining low nitrogen levels because tapping is fast and a tight tap stream is maintained. High oxygen potential in the steel is beneficial for low nitrogen levels, and the heat should be tapped open as opposed to blocking the heat.

Decarburization is also beneficial for the removal of hydrogen. It is demonstrated that decarburizing at a rate of 1% per hour can lower hydrogen levels in the steel from 8 ppm down to 2 ppm in 10 min.

At the end of refining, a bath temperature measurement and a bath sample are taken. If the temperature is too low, power to the bath may be increased. This is not a big concern in modern mills, where temperature adjustment is carried out in the ladle furnace.

Deslagging

Deslagging operations are carried out to remove impurities from the furnace. During melting and refining operations, some of the undesirable materials within the bath are oxidized and enter the slag phase.

It is advantageous to remove as much phosphorus into the slag as early in the heat as possible (i.e., while the bath temperature is still low). The furnace is tilted backward and slag is poured out of the furnace through the slag door. Removal of the slag at this stage eliminates the possibility of phosphorus reversion.

Phosphorus reversion is a phenomena that occurs during slag foaming operations; carbon may be injected into the slag where it will reduce FeO to metallic iron and in the process produce carbon monoxide to help foam the slag. If the high phosphorus slag has not been removed prior to this operation, phosphorus reversion will occur. During slag foaming, slag may overflow the steel level in the EAF and flow out of the slag door.

The slag contains various oxides and also some elements that are harmful to the steel. A typical analysis of EAF slag is given in Table 1-5-1.

Table 1-5-1 Electric arc furnace slag.

Component	Source	Composition range (%)
CaO	Charged	40–60
SiO_2	Oxidation product	5–15
FeO	Oxidation product	10–30
MgO	Charged as dolomite	3–8
CaF_2	Charged-slag fluidizer	
MnO	Oxidation product	2–5
S	Absorbed from steel	
P	Oxidation product	

Tapping

Once the desired steel composition and temperature are achieved in the furnace, the tap-hole is opened, the furnace is tilted, and the steel is poured into a ladle for transfer to the next operation. During the tapping process, bulk alloy additions are done, and additions are based on the bath analysis and the desired steel grade. Prior to further processing, deoxidizers are added to the steel at this point to lower the oxygen content. This is commonly referred to as "blocking the heat" or "killing the steel." Common deoxidizers are aluminum or silicon in the form of ferrosilicon or silicomanganese. Most carbon steel operations aim for minimal slag carryover. A new slag cover is "built" during tapping. For ladle furnace operations, a calcium aluminate slag is a good choice for sulfur control. Slag-forming compounds are added in the ladle at tap so that a slag cover is formed prior to transfer to the ladle furnace. Additional slag materials may be added at the ladle furnace if the slag cover is insufficient.

Basic oxygen furnace (BOF)

The BOF process uses 25%–35% old steel to make new steel. Oxygen steel-making process is one of the most common and efficient steel production methods. A brief discussion of the process is included in the following paragraphs.

The oxygen steel-making process is a generic name given to those processes in which gaseous oxygen is used as the primary agent for autothermic generation of heat as a result of the oxidation of dissolved impurities like carbon, silicon, manganese, and phosphorus, and to a limited extent the oxidation of iron itself. Several types of oxygen steel-making processes are practiced, such as top blowing, bottom blowing, and combined blowing, which have been invented.

The essential features of conventional steelmaking are the partial oxidation of the carbon, silicon, phosphorus, and manganese present in pig iron and the accompanying reduction in the sulfur level. Blast furnace hot metal for Linz-Donawitz (LD) BOF steel-making process ideally has the following analysis:

- Carbon = 4.2%
- Silicon = max 0.8%
- Manganese = max 0.8%
- Sulfur = max 0.05%
- Phosphorous = max 0.15%

These solute elements are diluted by the addition of scrap, which forms some 20%–30% of the metallic charge.

Refining reactions

In LD basic oxygen steel-making process, the oxygen required for the refining reactions is supplied as a gas, and both metal and slag are initially oxidized in the following reactions:

$$\tfrac{1}{2}O_{2(g)} \leftrightarrow [O] \qquad [1]$$

$$Fe + [O] \leftrightarrow (FeO) \qquad [2]$$

$$2(FeO) + \tfrac{1}{2}O_{2(g)} \leftrightarrow (Fe_2O_3) \qquad [3]$$

Carbon

The actual distribution of oxygen between slag and metal is not easily determined as it is a function of a number of variables including lance height and oxygen flow rate. The principal refining reactions is of course the removal of carbon as described by the following reactions:

$$[C] + [O] \leftrightarrow CO_2 \qquad [4]$$

$$[C] + (FeO) \leftrightarrow CO_2 + Fe \qquad [5]$$

Figure 1-5-1 represents an idealized diagram showing the changes in concentrations of the elements in an LD metal bath during oxygen blowing. The basic thermodynamic data for these reactions are well established and the equilibrium carbon and oxygen contents may be readily calculated for all temperatures and pressures encountered in steelmaking.

Oxidation of carbon during the oxygen converter process is most important, because the reaction increases the temperature and evolves a large amount of CO and CO_2 gases that cause agitation of metal and slag and helps remove hydrogen, nitrogen, and part of the nonmetallic inclusions from the metal. Owing to the pressure of the oxygen supplied and the evolution of large quantities of gases, the liquid bath becomes an intimate mixture of slag, metal, and gas bubbles, with an enormous

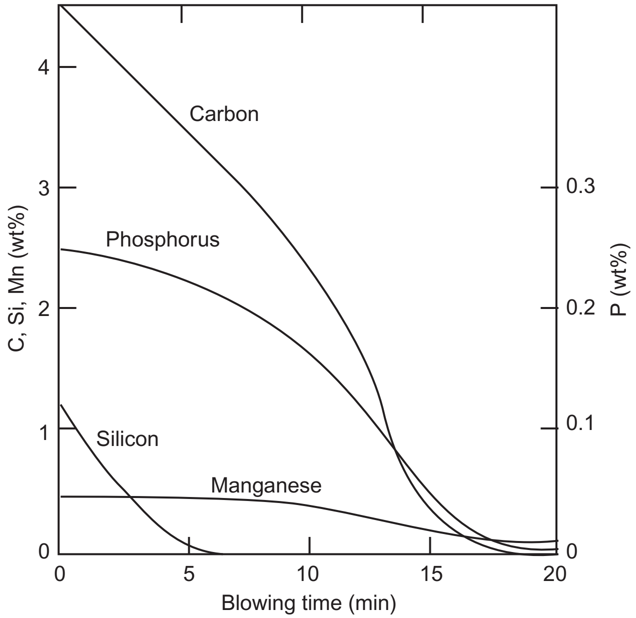

Figure 1-5-1 The changes of bath composition during the blow in a basic oxygen steel-making converter (idealized).

contact surface. Because of this, the reaction of carbon oxidation is self-accelerated and attains a very high rate.

Silicon

In accordance with thermodynamic predictions, the removal of silicon is usually completed relatively early in the blow. The typical reaction is represented by Equations [6] and [7] given here:

$$[\mathrm{Si}] + 2[\mathrm{O}] \leftrightarrow (\mathrm{SiO_2}) \qquad [6]$$

$$[\mathrm{Si}] + 2(\mathrm{FeO}) \leftrightarrow (\mathrm{SiO_2}) + 2\mathrm{Fe} \qquad [7]$$

Manganese

Similar equations can be applied to manganese removal:

$$[\mathrm{Mn}] + [\mathrm{O}] \leftrightarrow (\mathrm{MnO}) \qquad [8]$$

$$[\mathrm{Mn}] + (\mathrm{FeO}) \leftrightarrow (\mathrm{MnO}) + \mathrm{Fe} \qquad [9]$$

Initially the level of manganese in the bath falls due to the oxidation but later a slight reversion occurs and this is followed by a second fall in level. These changes in the manganese content of the bath are attributed to the combined effects of rising temperature and variable slag composition and reactions of manganese and ferrous oxides suggesting that the reaction is close to equilibrium. This view is supported by the observation that at the end of blowing the manganese content is found to be about 82% of the equilibrium value when lump lime is used and 85% of the equilibrium value when powdered lime was injected.

In the middle part of blow, the (FeO) level in the slag falls as a consequence of the decarburization process and the dilution that accompanies lime fluxing. However, toward the end of the blow, the (FeO) increases again, as carbon removal becomes less intense and dilution begins to affect the activity of manganese oxide with the result that manganese transfers from bath to slag. To some extent raising the temperature may minimize the manganese loss.

Phosphorus

The partitioning of phosphorus between the slag and metal is known to be very sensitive to process conditions, and so far some research laboratories associated with steel mills have been able to build a kinetic model based on simple assumptions.

Healy has reviewed the distribution of phosphorus between slag and metal. He concluded that the thermodynamic behavior of phosphorus is best explained by a modified version of the ionic theory first proposed by Flood and Grjotheim. The slag-metal reaction is written in ionic form in this equation:

$$2[P]+5[O]+3\left(O^{2-}\right)\leftrightarrow 2\left(PO^{3-}\right)_4 \qquad [10]$$

Healy has expressed the equilibrium distribution of phosphorus by equations that apply to specific concentration ranges in the CaO-SiO$_2$-FeO system:

$$\log\ (\%P)/[P]=22{,}350/T+7\ \log\%CaO+2.5\ \log Fe_t-24.0 \qquad [11]$$

$$\log\ (\%P)/[P]=22{,}350/T+0.08\ \log\%CaO+2.5\ \log Fe_t-16.0 \qquad [12]$$

Equation [11] applies to slag with CaO > 24% and Equation [12] is for slag containing CaO from zero percentage to saturation level.

In practice, the phosphorus partition ratios are far from the values calculated for equilibrium with carbon-free iron, because the oxygen potential of the slag-metal system is influenced by decarburization. A limited correlation with the carbon content in the bath has been reported, although other mills have suggested that extensive dephosphorization should be possible at high carbon levels, provided that the slag is sufficiently basic.

On the other hand, the dependence of phosphorus distribution on the FeO content of slag in LD and Q-BOP is shown in Figure 1-5-2. A parameter k_{PS} is defined as:

$$k_{PS}=(\%P_2O_5)/[\%P]\bullet(1+(\%SiO_2))=\varphi\,((\%FeO),B) \qquad [13]$$

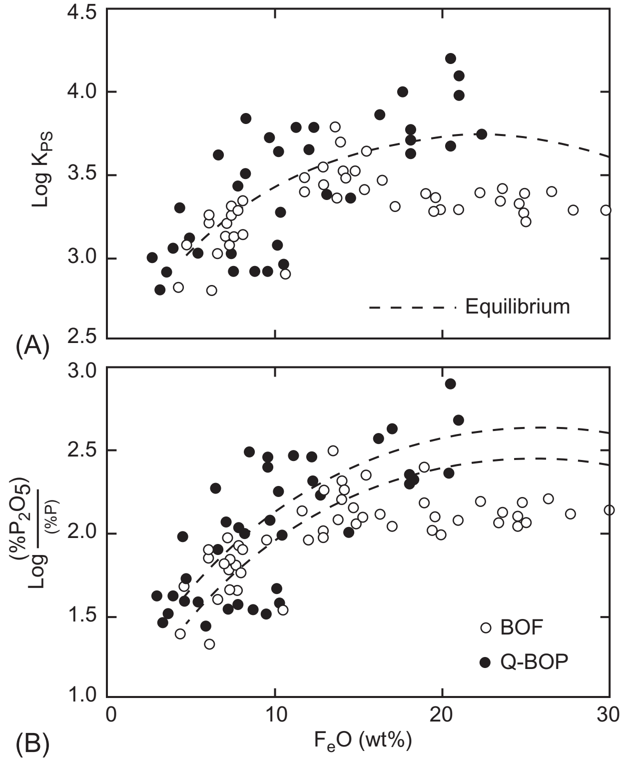

Figure 1-5-2 Effect of FeO content of slag on phosphorus distribution and log k_{PS} value. (A) Distribution at equilibrium; (B) Distribution at BOF and Q-BOP.

where,

B is basicity; for $B > 2.5$, k_{PS} is found to be independent of B.

The distribution of phosphorus is also found to be related to the content of carbon in steel at the time of tapping; owing to lower carbon levels achieved in bottom-blown process, the phosphorus distribution is expected to be better than in LD. In general, high basicity and the low temperature of slag (irrespective of the FeO content) favor dephosphorization.

Sulfur removal

Sulfur transfer takes place through the following reaction:

$$[S] + (O_2)_g = (SO_2)_g \qquad [14]$$

It is found that approximately 15%–25% of dissolved sulfur is directly oxidized into the gaseous phase due to the turbulent and oxidizing conditions existing in the jet impact zone

In BOF, the metal desulphurization proceeds slowly because it is a diffusion process. It may be accelerated to an extent by improving the bath mixing and increasing the temperature, fluidity, and basicity of the slag, and the activity of sulfur. At the initial stage of the heat, when the metal is rich in carbon and silicon, the activity of sulfur is high. Also, part of the sulfur is removed at the initial stages of the process when the temperature of melt is still relatively low through its reaction with manganese as the following reaction suggests:

$$[\mathrm{Mn}] + [\mathrm{S}] = (\mathrm{MnS}) \qquad [15]$$

A rise in the concentration of iron oxides in the slag promotes dissolution of lime, which favors desulphurization. The secondary and most intensive desulphurization occurs at the end, and at the heat when the lime dissolves in the slag with a maximum rate and the slag basicity (B) reaches 2.8 and more. Thus the total desulphurization of the metal is mainly decided by the basicity of the homogeneous final slag, which is formed in the oxygen converter process during the last minutes of metal blowing.

With an increase of slag basicity, the residual concentration of sulfur in metal bath becomes lower, allowing the coefficient of sulfur distribution between slag and metal to be raised up to 10. The greater bulk of slag is the largest part of the sulfur that will pass into slag at the same sulfur distribution coefficient. But there is a limit to the benefits of a very large bulk of slag, as this increases the iron loss due to burning, and causes splashing and rapid wear of the lining.

In a steel plant, regression equations based on operational data are employed to predict the end point of sulfur within acceptable limits. One such equation, for example:

$$(\%\mathrm{S})/[\mathrm{S}] = 1.42\mathrm{B} - 0.13(\%\mathrm{FeO}) + 0.89 \qquad [16]$$

Equation [16] shows the beneficial influence of slag basicity and the retarding influence of FeO on sulfur distribution. A large number of such correlations are reported in the literature, but they are suitable and applicable to a local situation only.

Deoxidation of steel

Deoxidation is the process that allows for the removal of excess oxygen from molten metal. The procedure involves adding a carefully measured amount of such materials that have high affinity for oxygen. They attract the oxygen present in the molten steel and form oxides, thus reducing the oxygen content in steel. The oxides of these materials are either removed in gaseous form or they readily form slag and float on the molten-steel surface, which is skimmed off. Deoxidation of steel is usually performed by adding manganese (Mn), silicon (Si), and aluminum (Al); other deoxidizers used are chromium (Cr), vanadium (V), titanium (Ti), zirconium (Zr), and boron (B), with the exception of chromium and special alloy-steels as the presence of these elements is not desirable, hence they are very rarely used and often in combination with the primary deoxidation elements given earlier.

As stated before, the deoxidizing agents have high affinity to oxygen This essential property of deoxidizing agents is exploited to remove excess oxygen from molten steel, but if not carefully controlled, the same property presents a paradox in the deoxidation of molten steel in that, by increasing the concentration of deoxidizer in the melt over certain critical limit, the process reverses to reoxidation of steel.

Deoxidation is the last stage in the steel-making process. In the BOF and other similar steel-making practices, the steel bath at the time of tapping contains 400–800 ppm activity of oxygen. Deoxidation is carried out during tapping by adding appropriate amounts of ferromanganese, ferrosilicon, and/or aluminum or other special deoxidizers into the tap-ladle. If at the end of the blow the carbon content of the steel is below specifications, the metal is also recarburized in the ladle. However, such last-minute additions are for fine adjustment; large additions in the ladle are undesirable, because the process brings down the temperature of the steel bath. Once the steel bath is according to the specified requirements, the steel is often poured into fixed molds to cast as ingots. In continuous casting process, the molds are in continuous movement, and the solidification takes place while the mold is in motion.

Although most of the steel in modern production process is produced through continuous casting methods where ingot production is not applicable, steel mills do produce ingots for secondary steel production markets. It helps to understand the production process and some terminologies through understanding the ingot process of steelmaking.

Eight typical conditions of commercial ingots, cast in identical bottle-top molds, in relation to the degree of suppression of gas evolution are shown schematically in Figure 1-5-3. The dotted line on the top indicates the height to which the steel originally was poured in each ingot mold. Depending on the carbon content and the oxygen content, the ingot structures ranges from that of a fully killed or dead-killed ingot N°1 in Figure 1-5-3 to that of a violently rimmed ingot N°8. Included in the series are killed steel marked N°1, semikilled steel marked N°2, capped steel N°5, and rimmed steel N°7.

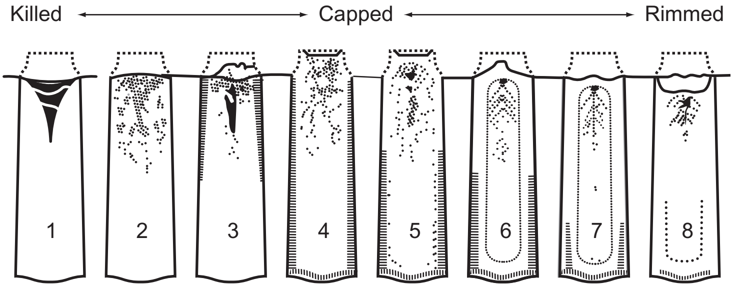

Figure 1-5-3 Series of typical ingot structures.

Rimmed steel

Rimmed steels are usually tapped without additions of deoxidizers to the steel in the furnace or only small additions to the molten steel in the ladle. This is done to have sufficient presence of oxygen to facilitate gas evolution by reacting in the mold with carbon. The exact procedures followed depend upon whether the steel has higher carbon content in the ranges of 0.12%–0.15%, or in the lower ranges of $\leq$0.10%. When the metal in the ingot mold begins to solidify, there is a brisk evolution of carbon monoxide, resulting in an outer ingot skin of relatively clean metal low in carbon and other solutes. Such ingots are best suited for the manufacture of steel sheets.

Capped steel

Production of capped steel is a variation of rimmed steel production practice. The rimming action is allowed to begin normally, but it is then terminated after about a minute by sealing the mold with a cast-iron cap. In steels with carbon content greater than 0.15%, the capped ingot practice is usually applied to the production of sheet, strip, wire, and bars.

Semikilled steel

Semikilled steel is deoxidized less than killed steel. This results in the presence of just enough oxygen in the molten steel; this oxygen reacts with carbon forming sufficient carbon monoxide to counterbalance the solidification shrinkage. This type of steel generally has carbon content within the range of 0.15%–0.30% and finds wide application in structural shapes.

Killed steel

Killed steel is deoxidized to such an extent that there is no gas evolution during solidification. Aluminum together with ferroalloys of manganese and silicon is used for deoxidation. In some applications, calcium silicide or other special strong deoxidizers are also used. To minimize piping, almost all killed steels are cast in hot-topped big-end up molds.

Killed steels are generally used when a homogeneous structure is required in the finished steels. Alloy steels, forging steels, and steels for carburizing are this type of steel. The steel requiring deep drawing and certain extra-deep-drawing steels with low-carbon up to maximum 0.12% is of this grade. For killing, these steels usually have a substantial amount of aluminum added in the ladle, in the mold, or both.

Deoxidation of steel by aluminum suppresses the formation of carbon monoxide during solidification, which controls formation of blowholes. There are many steel-processing operations where aluminum killing of steel is undesirable. Steels that are required for large castings are not killed with aluminum, because the suppression of carbon monoxide gas causes piping defects; inclusions of alumina also causes defective castings.

It has been recognized from the early days of continuous-casting operation that casting difficulties and poor surface conditions are often experienced with aluminum-killed steels. Hence, other forms of deoxidation are preferred over aluminum-killed steel. The alternative options may include silico-managanese deoxidation and/or vacuum carbon deoxidation.

Deoxidation equilibria

In the previous paragraphs of this chapter, we discussed the importance of the type and limitation of deoxidation. Let us now discuss the physics of the process.

Deoxidation reactions can be described using the deoxidation equilibrium constant. A wide spectrum of deoxidation equilibria pertaining to the most common deoxidants for steel is summarized in Table 1-5-2; the table is a log-log plot of the concentration of oxygen in solution in liquid steel against that of the added elements.

In all cases that we have discussed earlier, the oxygen and the alloying element in solution are in equilibrium with the appropriate gas, liquid, or solid oxide phases at 1600°C, e.g., 1 atm CO, pure B_2O_3, pure Al_2O_3, etc.

Table 1-5-2 Solubility of the products of deoxidation in liquid iron.[a]

Equilibrium constant K[a]	Composition range	K at 1600°C	log K
$[a_{Al}]^2[a_O]^4$	<1 ppm Al	1.1×10^{-15}	$-71{,}600/T + 23.28$
$[a_{Al}]^2[a_O]^3$	<1 ppm Al	4.3×10^{-14}	$-62{,}780/T + 20.17$
$[a_B]^2[a_O]^3$		1.3×10^{-8}	
$[a_C]\ [a_O]^3$	$>0.02\%$ C	2.0×10^{-3}	$-1168/T - 2.07$
$[a_{Cr}]^2[a_O]^3$	$>3\%$ Cr	1.1×10^{-4}	$-40{,}740/T + 17.78$
$[a_{Mn}]\ [a_O]$	$>1\%$ Mn	5.1×10^{-2}	$-14{,}450/T + 6.43$
$[a_{Si}]\ [a_O]^2$	>20 ppm Si	2.2×10^{-5}	$-30{,}410/T + 11.59$
$[a_{Ti}]\ [a_O]^2$	$<0.3\%$ Ti	2.8×10^{-6}	
$[a_{Ti}]\ [a_O]$	$>5\%$ Ti	1.9×10^{-3}	
$[a_V]^2[a_O]^4$	<0.10 V	8.9×10^{-8}	$-48{,}060/T + 18.61$
$[a_V]^2[a_O]^3$	$>0.3\%$ V	2.9×10^{-6}	$-43{,}200/T + 17.52$

Square brackets [ ] denote component present in molten steel.
Temperature (T) is on the Kelvin scale.
[a] Activities are chosen such that $a_{Mn} \equiv \%Mn$ and $a_O \equiv \%O$ when $\%M \rightarrow O$.

Deoxidation reactions can be described using the deoxidation equilibrium constant. The reaction when the alloying element (M) is added to the steel can be represented by Equation [17]:

$$M_xO_y = xM + Yo \qquad [17]$$

The deoxidation constant assuming pure M_xO_y forms is given in Equation [18]. The term pure M_xO_y describes the unit activity for M_xO_y:

$$K = (h_M)^x (h_O)^y \qquad [18]$$

where h_M and h_O are the Henrian activities. These are defined as the activity of the components is equal to its weight percent at infinite dilution in iron, as given by Equation [19]:

$$H_i = f_i(wt\%i) \qquad [19]$$

The activity coefficient f_i can be corrected for alloying elements by use of the interaction parameter $e^j{}_i$, which is defined by following equation:

$$(d \log f_i / d \log wt\%j) = e^j{}_i \qquad [20]$$

Table 1-5-3 is the collection of data for carbon steel and stainless steel. It shows the coefficients of interaction for the common elements of carbon and stainless steels at 1600°C (2912°F).

The activity coefficient for most low alloy steels encountered in ladle metallurgy is taken as unity, and Equation [18] is reduced to the following:

$$K_M = (\%M)^x (\%O)^y \qquad [21]$$

To illustrate how to use these constants, let us consider a steel that contains silicon (0.1%) at 1600°C (2912°F) in equilibrium with SiO_2. In this case, the value of K_{Si} is given by following equation:

$$K_{Si} = (\%Si)(\%O)^2 \qquad [22]$$

$$K_{Si} = 2.2 \times 10^{-5}$$

Therefore:

$$(\%O)^2 = 2.2 \times 10^{-4}$$

$$(\%O) \approx 0.015 \text{ or } 150\,\text{ppm}.$$

It is important to note that these calculations are for soluble oxygen content; the total oxygen content that includes both the soluble oxygen and the oxygen associated with inclusions could be much higher.

Table 1-5-3 The coefficients of interaction for the common elements of carbon and stainless steels at 1600°C.

Metal		Al	C	Mn	P	S	Si	Ti	H	N	O	Cr	Ni
Carbon steel	$\%_i$		0.05	0.45	0.02	0.01	0.3	0.05					
	f_i	1.05	1.06	1.0	1.1	1.0	1.15	0.93	1.0	0.97	0.85		
	a_i		0.053	0.45	0.022	0.01	0.345	0.046					
Stainless steel	$\%_i$		0.05	0.45	0.02	0.01	0.3	0.05				18	8
	f_i	3.6	0.49	1.0	0.32	0.66	1.24	9.4	0.93	0.17	0.21	0.97	1.0
	a_i		0.025	0.45	0.006	0.007	0.372	0.47				17.5	8.0

For single element deoxidation, the solubility of oxygen in liquid iron at 1600°C (2912°F) is given as a function of the concentration of the alloying element. In each case, the melt is in equilibrium with the respective pure oxide, such as SiO_2, Al_2O_3, etc. It can be clearly seen that aluminum is the strongest of the common deoxidizers, followed by titanium. Rare earths are also strong deoxidizers, such as aluminum, but their use is limited to control radiation.

Practical case emphasizing the importance of deoxidation of steel for critical welding applications

Oxygen removal and inclusion control during deoxidation process in steelmaking cannot be overemphasized for welding engineering applications. In one recent application, excessive repairs in the welds were caused due to deoxidizing issues related to a specific heat of steel pipes. The pipe welding was in fixed horizontal position, and a very stringent level of tests was carried out to qualify the welding procedures and welding operators. There were very nominal repair issues during the qualification process. The heats of pipes used during qualification were also used with other heat of steel during the production process. The analysis of weld defects pointed to one specific heat of pipe that was not used in the qualifications process. More than 78% of all weld repairs involved this specific heat of pipes.

The type of defects found in automatic ultrasonic testing (AUT) included following:

• Internal concavity	4%
• Cold Lap or incomplete fusion	2%
• Bottom of pipe tie-in incomplete fusion	27%

A majority of these weld defects were determined to be due to the residual oxygen level and dispersal of inclusion associated with the specific heat of the steel (pipe). These are indicative of the process control and quality of steelmaking. The two issues associated with the deoxidation process during steelmaking are:

(1) Amount of oxygen present in steel
(2) The type, shape, and dispersion of inclusions

Both these issues are directly related to the deoxidizing processes practiced in steelmaking. As discussed earlier, the elements silicon (Si), aluminum (Al), manganese (Mn), and calcium (Ca) are used individually or in combination to remove oxygen from steel. When a combination of elements is used, it is called complex oxidation process; this includes use of Si, Mn, Al, and Ca.

These deoxidation elements added directly or through their ferroalloys work differently and have different levels of effectiveness in oxygen removal. Their interactions with each other and other additions, the temperature, flow rate, ability to float, interaction with slag, etc. make the process very complex. Some elements form solid compounds, whereas others form liquid or gas compounds, but all these need to be removed effectively to an acceptable level. All these play important roles on how much residual oxygen is in the steel.

The kinetics of deoxidation dictates the amount of oxygen left in the steel. The dilution, homogenization, and growth mechanism of dissolution play their role in nucleation of solids, such as Al_2O_3 and its interface with steel. The removal of deoxidation products are as important a part of the kinetics of deoxidation as are the floatation and absorption into slag, movement through the steel to the surface, and its absorption in any synthetic slag used in the process. The floatation is dependent on physical properties of steel, size of oxidation product, rate of rise of particles, and type of flow, which affects the Reynolds number. All these have bearing on the two issues identified earlier.

All the previous discussed factors are part of the steel-making process that are normally not reported on a material test report (MTR) provided by steel mills. These can be verified only by a detailed audit of the steel-making process related to the production of specific heat.

As stated, for welding this information is very critical; the mere use of the term “Killed Steel” does not address the importance of this subject to the welding engineer. This is because the level of residual oxygen and dispersal of inclusions are not reported in any MTR. The level of residual oxygen and dispersal of inclusions are, in part, the result of interaction between these deoxidizing elements that happens in the molten stage of the steel. After the steel is made, it is only during the welding process that the steel melting temperature range is experienced, and the effects of level of residual oxygen in steel and quality of oxidation practiced can be known. Thus for critical welding applications where very high standards of weld quality is desired, a welding engineer should evaluate the steel for its oxygen removal practices and obtain information on residual oxygen level and dispersal of inclusions.

Iron-iron carbide phase diagram

Iron is an allotropic metal; it can exist in more than one type of lattice structure depending on the temperature. The temperature at which the changes occur depends on the alloying elements in iron, especially that of carbon content.

The iron-carbon phase diagram that we have discussed in previous chapter is a good basis for understanding the effect of temperature and components affecting the properties of steel. The portion of the diagram between pure iron and an interstitial compound Fe_3C (iron carbide) is of significance.

Classification of steels

6

Steels are classified by a variety of different systems depending on the following parameters.

- The composition, such as carbon, low-alloy, or stainless steel
- The manufacturing methods, such as open hearth, basic oxygen process, or electric furnace methods
- The finishing method, such as hot rolling or cold rolling
- The product form, such as bar plate, sheet, strip, tubing, or structural shape
- The deoxidation practice, such as killed, semikilled, capped, or rimmed steel
- The microstructure, such as ferritic, pearlitic, and martensitic
- The required strength level, for example, as specified in various industry standards like API, ASTM/ASME, etc.
- The heat treatment, such as annealing, quenching, tempering, and thermomechanical processing, etc.
- Quality descriptors, such as forging quality and commercial quality (Figure 1-6-1)

Carbon steels

The American Iron and Steel Institute (AISI) defines carbon steel as steel that has no minimum specified content or requirements for chromium, cobalt, niobium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium, or specified requirement for any other element to be added specifically to obtain a desired alloying effect; in such steel, the specified copper should be within 0.40% and 0.60%, and the maximum limit for manganese shall not exceed 1.65% and silicon 0.60%.

Carbon steel is classified, according to deoxidation practices, as rimmed steel, capped steel, killed steel, or semikilled steel. We have discussed these types of steel in Chapter 5 of this book.

Steels are also classified based on carbon content. Carbon-steels contain up to 2% total alloying elements and are further divided into low-carbon steels, medium-carbon steels, high-carbon steels, and ultrahigh-carbon steels; each of these classifications is discussed in the following sections.

Low-carbon

Low-carbon steels contain up to 0.30% carbon. A majority of this class of steel is flat-rolled products like sheet or strip; usually they are in a cold-rolled and annealed condition. These steels have high formability as they contain very low carbon, usually less than 0.10% C, with up to 0.4% Mn.

Applied Welding Engineering. https://doi.org/10.1016/B978-0-12-821348-3.00014-8

AISI-SAE designation	Type of steel with typical grades	Nominal alloy content (%)		
Carbon steels				
10xx	Plain carbon steel: 1005, 1010, 1016, 1030 etc.	Manganese up to 1% max		
11xx	Resulfurized: 1110, 1117, 1137 etc.			
12xx	Resulfurized and Rephosphorized: 1211, 1212, 1213, 1215, 12L14 (this grade include up to 0.35% lead)			
15xx	Plain carbon steel: 1513, 1522, 1526, 1548,1561, and 1566 etc.	Manganese range from 1% to 1.65%		
Manganese steels				
13xx		Manganese 1.75%		
Nickel steels				
23xx		Nickel 3.5		
		Nickel 5		
Nickel-chromium steels				
31xx		Nickel 1.25, Cr 0.65 and 0.80		
32xx		Nickel 1.75, Cr 1.07		
33xx		Nickel 3.50, Cr 1.5 and 1.57		
34xx		Nickel 3.00, Cr 0.77		
Molybdenum steels				
40xx	4023, 4024, 4027, 4028 etc.	Mo 0.20 and 0.25		
44xx		Mo 0.40 and 0.52		
Chromium-molybdenum steels				
41xx		Cr	Mo	
	4118	0.50	0.12	
	4130, 4137, 4140, 4142, 4145, 4147, 4150	0.80	0.20	
		0.95	0.25	
	4161	0.70-0.90	0.30	
Nickel-chromium-molybdenum steels				
43xx	4320	Ni	Cr	Mo
		1.65 to 2.00	0.40 to 0.60	0.20 to 0.30
	4340	1.65 to 2.00	0.70 to 0.90	0.20 to 0.30
47xx	4720	0.90 to 1.20	0.35 to 0.55	0.15 to 0.25
81xx		0.30	0.40	0.12
86xx		0.55	0.50	0.20
87xx		0.55	0.50	0.25
88xx		0.55	0.50	0.35
93xx		3.25	1.20	0.12
94xx		0.45	0.40	0.12
97xx		0.55	0.20	0.20
98xx		1.00	0.80	0.25
Nickel-molybdenum steels				
46xx		Ni	Mo	
		0.85	0.20	
		1.82	0.25	
48xx		3.50	0.25	
Chromium steels				
50xx		Cr 0.27, 0.40, 0.50, 0.65		
51xx		Cr 0.80, 0.87, 0.92, 1.00, 1.05		
52xx		Cr 0.50, Carbon 1.00		

Figure 1-6-1 Classification of steel.

continued

	Chromium-vanadium steels		
61xx		Cr	V
		0.60, 0.80, 0.95	0.10, 0.15
Chromium-tungsten steels			
72xx		Cr 0.75; W 1.75	
Silicon-manganese steels			
92xx		Si: 1.40, 2.00; Mn 0.65, 0.82, 0.85; Cr 0.65	
High-strength low-alloy (HSLA) steels			
9xx		Various SAE grades	
xxBxx		B indicates added Boron	
xxLxx		L indicates Lead addition	
XX indicates steel designation for carbon steel and low alloys.			
Stainless steels			
AISI designation	SAE designation		
2xx	302xx	Chromium Manganese and	

Figure 1-6-1—cont'd

For rolled steel structural plates and sections, the carbon content is often increased to approximately 0.30% and manganese content increased to 1.5%. These materials are useful for stampings, forgings, seamless tubes, and boilerplates.

Medium-carbon

Medium-carbon steels are similar to low-carbon steels except they contain carbon from 0.30% to 0.60% and manganese from 0.60% to 1.65%. Increasing the carbon content to approximately 0.5% with an accompanying increase in manganese allows medium-carbon steels to be used in the quenched and tempered condition. These steels are mainly used for making shafts, axles, gears, crankshafts, couplings, and forgings. Steels with carbon ranging from 0.40% to 0.60% are used for rails, railway wheels, and rail axles.

High-carbon

High-carbon steels contain carbon from 0.60% to 1.00%, and the manganese content ranges from 0.30% to 0.90%. High-carbon steels are used for some hand tools, spring materials, and high-strength wires, etc.

Ultrahigh-carbon

These steels are often experimental alloys containing 1.25% to 2.0% C. These steels are often thermomechanically processed to produce consistent and ultrafine microstructures that are equiaxed grains of spherical, discontinuous, proeutectoid carbide particles.

High-strength low-alloy steels (HSLA)

High-strength low-alloy (HSLA) steels are microalloyed steels; they are designed to provide better mechanical properties and may also have greater resistance to atmospheric corrosion as compared with conventional carbon steels.

The HSLA steels have low carbon contents (0.05%–0.25%) to produce adequate formability and weldability, and they have manganese contents up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium, and zirconium are added in various combinations to impart specific properties.

Classification of high-strength low-alloy steels

Weathering steels are designated to exhibit superior atmospheric corrosion resistance.

Control-rolled steels are hot rolled in accordance with a predetermined rolling schedule. These steels are designed to develop a highly deformed austenite structure that, on cooling, transforms into a very fine equiaxed ferrite structure.

Pearlite-reduced steels are strengthened by very fine-grain ferrite and precipitation hardening but with low carbon content and therefore little or no pearlite in the microstructure.

Microalloyed steels have very small additions of such elements as niobium, vanadium, and titanium for refinement of grain size or precipitation hardening. Often apart from the individual amount of these elements, the combined total of these alloys is also limited.

Acicular ferrite steel has very low carbon content and develops sufficient hardenability when cooling to transform to a very fine high-strength acicular ferrite structure rather than the usual polygonal ferrite structure.

HSLA steels may also have small additions of calcium, rare earth elements, or zirconium for sulfide inclusion shape control.

Although not specifically classified as HSLA steel, another class of material that has emerged and is being used in the design and construction of oil and gas pipelines can be treated as HSLA to a degree. The common points in the HSLA steel as described earlier and the high-strength steels used for making line pipes are called API 5L/ISO 3183 in that these steels have low alloying elements and exhibit very high yield strength. The special difference is that the line pipe steels have some very fine alloying practices called microalloying. This includes the use of the mass fraction carbon that is often limited to 0.18% for seamless pipes and 0.12% for welded pipes. The alloying elements are controlled to obtain weldability of the steel during construction. The main microalloying elements are titanium, vanadium, and niobium. These elements are added to obtain specific properties in the steel; however, their combined total is also restricted to a maximum 0.15% of the total mass fraction.

The practice of microalloying combined with special rolling practices gives steel special strength and toughness properties to meet design requirements. These high-strength steels commonly display yield strength of over 60 ksi and tensile strength of over 110–166 ksi. Of course, such varied ranges are grouped in different grades based on steels' yield strength. These grades range from X-60, X-65, X-70, X-80, X-90, X-100, and X-120; the prefix X in these cases indicates that the number succeeding the letter if multiplied by 1000 will give the specified minimum yield strength (SMYS) of the particular grade of steel.

For example:

$$\text{Grade X} - 60 \text{ means that the steel has an SMYS of } 60 \times 1000 = 60{,}000 \text{ psi.}$$

There are lots of other grades and information relating to various requirements of line pipe materials. For more information and details, interested readers must obtain a copy of the latest edition of API 5L/ISO 3183.

Low-alloy steels

Low-alloy steels constitute a category of ferrous materials that exhibit mechanical properties superior to plain carbon steels due to the addition of alloying elements such as nickel, chromium, and molybdenum. Total alloy content can range from 2.07% up to levels just below that of stainless steels, which contain a minimum of 10% chromium.

For many low-alloy steels, the primary function of the alloying elements is to increase hardenability to optimize mechanical properties and toughness after heat treatment. In some cases, however, alloy additions are to reduce environmental degradation under certain specified service conditions. As with steels in general, low-alloy steels can be classified according to the **chemical composition**, such as nickel steels, nickel-chromium steels, molybdenum steels, and chromium-molybdenum steels.

They are also classified based on **heat treatment**, such as quenched and tempered, normalized and tempered, and annealed.

Because of the wide variety of chemical compositions possible and the fact that some steels are used in more than one heat-treated, condition, some overlap exists among the alloy steel classifications. Four major groups of alloy steels are identified and discussed here.

Low-carbon quenched and tempered steels

Theses steels combine high yield strength, ranging from 50 to 150 ksi (350–1035 MPa) and good notch toughness ductility, corrosion resistance, or weldability. There are different combinations of these steels with varying characteristics based on their intended applications.

Medium-carbon ultrahigh-strength steels

These are structural steels with yield strengths that can exceed 200 ksi (1380 MPa). Many of these steels are covered by SAE/AISI designations or are proprietary compositions. Product forms include billet, bar, rod, forgings, sheet, tubing, and welding wire, etc.

Bearing steels

Bearing steels, as the name suggests, are used for ball and roller bearing applications. They contain low carbon, about 0.10%–0.20%, and these steels are case-hardened. Many of these steels are covered by SAE/AISI designations.

Chromium-molybdenum heat-resistant steels

Chromium-molybdenum heat-resistant steels contain 0.5%–9% chromium and 0.5%–1.0% molybdenum. The carbon content is usually below 0.2%. Chromium provides improved oxidation and corrosion resistance, and the molybdenum increases strength at elevated temperatures. They are generally supplied in the normalized and tempered, quenched and tempered, or annealed condition. Chromium-molybdenum steels are widely used in the oil and gas industries, and in fossil fuel and nuclear power plants.

As stated earlier, steels may be classified by method of manufacture, their use, or by chemical composition. Manufacturing method categories include Bessemer steel, open-hearth steel, electric-furnace steel, crucible steel, etc. Some steel specifications specify the particular method required to comply with a standard. Classification based on "use" include machine steel, spring steel, boiler steel, structural steel, or tool steel. Classification by chemical composition is the most common method. Steel specifications systems are generated by AISI and SAE in the United States; they use an elaborate numbering system to indicate the approximate alloying content.

Sometimes letter prefixes are included to designate the steel-making process (B = acid Bessemer, C = basic open-hearth, E = basic electric furnace). The last two numbers indicate the carbon content, for example, the AISI 1020 steel has 0.20% carbon. The following is the list of some AISI steels and their general descriptions. For more detailed information about any of these steels, refer to the AISI publication.

AISI series

- 10xx Basic open-hearth and acid Bessemer carbon steels
- 11xx Basic open-hearth and acid Bessemer carbon steels, high sulfur, low phosphorous
- 12xx Basic open-hearth carbon steels, high sulfur, high phosphorous
- 13xx Manganese 1.75%
- 40xx Molybdenum 0.20% or 0.25%
- 41xx Chromium 0.50%, 0.80%, or 0.95%; molybdenum 0.12%, 0.20%, or 0.30%
- 43xx Nickel 1.83%, chromium 0.50% or 0.80%, molybdenum 0.25%

- 46xx Nickel 0.85% or 1.83%, molybdenum 0.20% or 0.25%
- 47xx Nickel 1.05%, chromium 0.45%, molybdenum 0.20% or 0.35%
- 48xx Nickel 3.5%, molybdenum 0.25%
- 51xx Chromium 0.80%, 0.88%, 0.93%, 0.95%, or 1.00%
- 5xxxx Carbon 1.4%, chromium 1.03% or 1.45%
- 61xx Chromium 0.60% or 0.95%, vanadium 0.13% or 0.15%
- 86xx Nickel 0.55%, chromium 0.50%, molybdenum 0.20%
- 87xx Nickel 0.55%, chromium 0.50%, molybdenum 0.25%
- 88xx Nickel 0.55%, chromium 0.50%, molybdenum 0.35%
- 92xx Silicon 2.00%

Material classification through the processing methods

The material produced though the processes discussed earlier can be further divided on the basis of secondary processing methods. These secondary processes often play a very important role in the material's weldability; thus, these are important factors to be aware of when planning a welding procedure for a specific steel. These properties of steel cannot be ignored by a welding engineer when setting up a welding procedure, cold or hot forming, and necessary heat treatments.

The term *secondary processing* here is used to distinguish it from secondary steel-making, which is also referred as *ladle metallurgy*. Ladle metallurgy is a process associated with clean steel-making process, wherein the process follows after the steel from converter or electric arc furnace (EAF), which may involve deoxidation, decarburization, and fine chemical adjustment of fine alloying elements or even the gases in the steel.

Thus, secondary processing is the mechanical processing of steel to meet the final properties. This process is often after the initial steel is produced, and no more molten stage of steel is achieved. Rolling, Coiling, Thermomechanical processing (TMCP); Cold-rolled steel, Interstitial-free steels, High-strength low-alloy steels (HSLA), and Ultralow plain carbon steels are a few such names to know.

Recrystallization rolling

The rolling itself can be of various types to achieve different steel properties. The process involves recrystallization of austenite at successively low temperatures. The recrystallization-controlled rolling, at relatively low temperature of 750–900°C, refines the austenitic grain size to as low as 8 to10 μm. The addition of vanadium to steel (at the steel-making stage) is advantageous as the carbide of vanadium readily dissolves at rolling temperature and is unavailable for suppressing the recrystallization process.

Compared with the vanadium steels, the niobium steels can undergo recrystallization-controlled rolling at higher temperatures with the forming of Nb(C,N) precipitates. This formation of niobium carbo-nitride (Nb(C,N)) is instrumental in restricting austenite grain growth. This restrictive ability of Nb(C,N) eliminates the use of titanium addition in niobium-alloyed steels.

Dynamic recrystallization-controlled rolling

The dynamic recrystallization-controlled steels are those that are given very little time between rolling processes to achieve austenite grain size of $\leq 10\,\mu m$. The restriction of time between the rolling processes initiates the recrystallization process, due to heavy reduction in the section, up to 100% reduction is carried out. Because the process is carried out at low temperature, fine ferrite (as low as 3–6 μm) grains result.

These low temperature gain controls and refining with microalloying results in very complex metallurgy of steel, which demands special attention from welding engineers when planning welding and fabrication of these steels. The weldability of these steels are critical and requires specific knowledge to develop suitable welding procedures.

For example, heating of TMCP steel to above 580°C (1075°F) after steelmaking can reduce the steel's yield strength. This will require that the next process, such as making induction bends or other fittings out of pipes, is carried out below 850°C, or a suitable heat treatment is devised to restore the material's strength, or the initial material selected should be of higher strength to compensate for the loss of strength after the work is completed.

Due to their complex metallurgy, including the alloying elements and also the related processing, the resulting grain structure presents specific welding challenges. The welding challenges of some of the other steels such as HSLA and low-alloy steels (9 Cr steel for boiler tubes) are discussed in the case studies included with this book. The weldability of some other steels and alloys are discussed in subsequent chapters of this book.

Cast iron and cast steel

7

The term *cast iron* covers a family of ferrous alloys. It is an iron alloy that contains more than 2% carbon and silicon in the range of 1%–3%. The extent of alloying and associated control of the heating and cooling process can provide a very wide variety of properties to different grades of cast iron. In Figure 1-4-4, the correct position of cast iron is indicated to the right of steel at 2.1% carbon.

Types of cast iron

Cast iron is used in the oil and gas industry to make water conduit pipes, packer parts, boilers, valve bodies, and valve parts. Cast iron is the form of material favored by foundrymen over cast steel for following reasons.

1. The ease of production through cupola furnace
2. Lower melting temperature of cast iron in relation to steel
3. Excellent fluidity of molten cast iron

The construction of a cupola furnace is somewhat like a blast furnace; however, apart from its very different use, it is much smaller and less costly to operate. The furnace is charged with coke, pig iron scrap metal, and limestone as flux and slag former. Other elements are introduced in melt through addition of ferroalloys. Cast irons have low ductility, hence they cannot be rolled, drawn, or worked-on at room temperature. Most cast irons have lower strength than most steels. Cast irons are generally classified according to their microstructure. The microstructure depends on the carbon content, the alloy and impurity content, the cooling rate during and after freezing, and heat treatment after casting. The condition and physical form of the carbon controls the properties of cast iron.

The composition of cast iron varies significantly depending upon the grade of pig iron scrap used, but in general it contains high carbon in the range of about 2%–4% by weight. The other alloying elements are manganese (Mn), phosphorous (P), sulfur (S), and high silicon concentrations, and a much greater concentration of impurities than steels.

The mode and concentration of carbon in the cast iron is controlled to produce white cast iron, gray cast iron, or malleable cast iron. These forms of cast iron differ significantly from each other in their mechanical properties and weldability.

Both carbon and silicon influence the nature of iron castings. A factor called carbon equivalent (CE) determines the approximation of their impact on solidification. The impact of two elements can be determined by the following relationship:

$$\mathrm{CE} = \mathrm{C} + (\mathrm{Si}/3)$$

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For a more accurate assessment, the effect of phosphorous is also considered, and the formula is suitably modified to include phosphorus:

$$CE = C + (Si + P/3)$$

The comparison with iron and carbon (Fe-C) eutectic system (i.e., 4.3% C) and knowledge of the CE of the casting allows us to understand if the resulting cast iron will behave like hypoeutectic or hypereutectic upon solidification. If the CE value of the given casting is closer to the eutectic value of the casting, the liquid state will persist to a relatively low temperature and solidification would take place over a small temperature range. This is important because this would promote uniform properties in the casting.

In hypereutectic irons where the CE is greater than the eutectic value 4.3%, the tendency to form kish-graphite increases. The kish-graphite is the proeutectic graphite on formation that freely floats within the molten iron and precipitates on solidification on normal cooling conditions. In such iron, lower CE values would increase the chances of formation of white or mottled cast iron on solidification.

The CE of a cast iron also helps to distinguish the gray irons that cool into a microstructure containing graphite and the white irons where the carbon is present mainly as cementite.

A high cooling rate and low CE favors the formation of white cast iron, whereas a low cooling rate or a high CE promotes gray cast iron.

During solidification, the major proportion of the carbon precipitates in the form of graphite or cementite. When solidification is just complete, the precipitated phase is embedded in a matrix of austenite that has an equilibrium carbon concentration of about 2% by weight. Upon further cooling, the carbon concentration of the austenite decreases as more cementite or graphite precipitate from the solid solution. For conventional cast irons, the austenite then decomposes into pearlite at the eutectoid temperature. However, in gray cast irons, if the cooling rate through the eutectoid temperature is sufficiently slow, then a completely ferritic matrix is obtained with the excess carbon being deposited on the already existing graphite.

White cast iron

White cast iron is formed when, on solidification, carbon in solution is not able to form graphite White cast irons are hard and brittle; they cannot easily be machined. White cast iron is unique in that it is the only member of the cast iron family in which carbon is present only as carbide. Due to the absence of graphite, it has a light appearance. White cast iron has high compressive strength and retains good hardness and strength at a higher temperature. The presence of different carbides, depending on the alloy content, makes white cast irons extremely hard and abrasion resistant but very brittle. An improved form of white cast iron is the chilled cast iron, discussed further in this chapter.

Microstructure of white cast iron contains massive cementite (white) and pearlite. It contains interdendritic cementite (white), which sometimes has a Widmanstiitten ("spiky") appearance. Austenite forms as the proeutectic constituent before the eutectic reaction (liquid transforms to austenite and cementite) and later transforms to pearlite and cementite upon cooling below the eutectoid temperature, about 723°C (1333°F). White cast iron is named after its white surface when fractured due to its carbide impurities, which allow cracks to pass straight through.

Malleable cast iron

Also referred as malleable iron, the carbon in this class of cast iron is irregularly shaped graphite nodules instead of flakes. This is essentially a white cast iron that has been heat-treated to convert the iron carbide into the irregularly shaped graphite nodules. This form of graphite is called temper carbon because it is formed in the solid state during the heat treatment.

Although the cementite found in cast iron is considered to be metastable, heat treatment can cause it to transform into iron and carbon. Malleabilization is performed to convert all of the combined carbon in white iron into irregular nodules of graphite and ferrite. Two annealing stages are performed at about 899°C (1650°F) to 927°C (1700°F) for up to 72 h. A tough ferritic matrix surrounds the resultant temper carbon so malleable cast iron has higher strength and ductility than gray cast iron.

The malleable iron is classified in three grades:

1. Ferritic malleable
2. Pearlite malleable
3. Martensitic malleable

We shall briefly discuss each of these malleable irons in this text.

Ferritic malleable iron

This category of malleable iron has two types, white heart iron and black heart iron.

White heart cast iron

White heart cast iron is essentially cast as white cast iron and made malleable by annealing in an oxidizing medium; during the heat treatment, substantial decarburization occurs and the remaining carbon is precipitated in the form of graphite nodules. This type of iron normally contains about 0.6%–1.3% silicon, which is just enough to promote cementite decomposition during the heat treatment but not enough to produce graphite flakes during casting. White heart malleable iron is made by heating to a temperature of 900°C (1650°F), which is an oxidizing atmosphere to remove carbon from the surface of white iron castings.

Black heart cast iron

The black heart cast iron has a matrix of ferrite with interspersed nodules of temper carbon. In the Unites State, the term *cupola malleable iron* is used for type of black heart malleable iron produced from a cupola furnace and used for pipefitting, etc. The strength and ductility of this grade is very low, hence it is not very favored as a structural material.

Pearlite malleable cast iron

Pearlite malleable iron has combined carbon in the matrix, which results in higher strength and hardness than ferritic malleable iron.

The process involves controlling the carbon content and heat treatment cycle; some carbon can be retained as finely distributed iron carbide. This combined carbon increases the strength and hardness.

Martensitic malleable iron

Martensitic malleable iron is initially produced as pearlitic iron. It is subsequently quenched and tempered to make it martensitic malleable iron.

Gray cast iron

Gray cast iron is a broad term used for a number of cast irons whose microstructure is characterized by the presence of flake graphite in the ferrous matrix. Such castings often contain 2.5%–4% carbon, 1%–3% silicon, and some additions of manganese ranging from 0.1% to 1.2%.

This is one of the most widely used alloys of iron. The strength of gray cast iron depends on the matrix in which graphite (free carbon) is embedded. The matrix can range from ferrite to pearlite and various combinations of the two phases. Large graphite flakes reduce the strength and ductility, so inoculants are used to promote fine flakes.

Gray cast iron is named after its gray fractured surface, which occurs because the graphitic flakes deflect a passing crack and initiate countless new cracks as the material breaks. White cast irons are hard and brittle. Gray cast irons are softer with a microstructure of graphite in transformed-austenite and cementite matrix. The graphite flakes, which are rosettes in three dimensions, have a low density and hence compensate for the freezing contraction, thus giving good castings that are free from porosity.

The flakes of graphite have good damping characteristics and machinability because the graphite acts as a chip-breaker and lubricates the cutting tools. In applications involving wear, the graphite is beneficial because it helps retain lubricants. However, the flakes of graphite also are stress concentrators, leading to poor toughness. The recommended applied tensile stress is therefore only a quarter of its actual ultimate tensile strength.

Sulfur in cast irons is known to favor the formation of graphite flakes. The graphite can be induced to precipitate in a spheroidal shape by removing the sulfur from the melt using a small quantity of calcium carbide. This is followed by a minute addition of magnesium or cerium, which poisons the preferred growth directions and leads to isotropic growth resulting in spheroids of graphite. The calcium treatment is necessary before the addition of magnesium because the latter also has an affinity for both sulfur and oxygen, whereas its spheroidizing ability depends on its presence in solution in the liquid iron. The magnesium is frequently added as an alloy with iron and silicon (Fe-Si-Mg) rather than as pure magnesium.

However, magnesium tends to encourage the precipitation of cementite, so silicon in the form of ferrosilicon is also added to ensure the precipitation of carbon as graphite. The ferrosilicon is the inoculant in the system.

Gray cast iron is by far the oldest and most common form of cast iron. As a result, it is assumed by many to be the only form of cast iron, and the terms *cast iron* and *gray iron* are used interchangeably. Unfortunately the only commonly known property of gray iron—brittleness—is also assigned to “cast iron” and hence to all cast irons. Gray iron is so named because its fracture has a gray appearance. It contains carbon in the form of flake graphite in a matrix that consists of ferrite, pearlite, or a mixture of the two.

The fluidity of liquid gray iron, and its expansion during solidification due to the formation of graphite, has made this metal ideal for the economical production of shrinkage-free, intricate castings such as engine blocks.

The flake-like shape of graphite in gray iron exerts a dominant influence on its mechanical properties. The graphite flakes act as stress raisers, which may prematurely cause localized plastic flow at low stresses, and initiate fracture in the matrix at higher stresses. As a result, gray iron exhibits no elastic behavior and fails in tension without significant plastic deformation but has excellent damping characteristics. The presence of graphite flakes also gives gray iron excellent machinability and self-lubricating properties.

ASTM Specification A-48 lists several classes of gray cast irons based on tensile strength. A range from 20 ksi tensile strength to 60 ksi is identified.

Cast irons above 40 ksi tensile strength are considered high-strength irons.

Compressive strength is much more important than tensile strength for many applications, and, in many cases, gray cast iron performs better than steel in compression-loading applications.

Castability of gray cast iron

Two important parameters for a successful casting are the fluidity of molten metal and the cooling rate. These are also affected by thickness and variations in thickness of the section of casting. The term *section sensitivity* used to define the castability is an attempt to correlate properties in the critical sections with composition and the cooling rate (Figure 1-7-1).

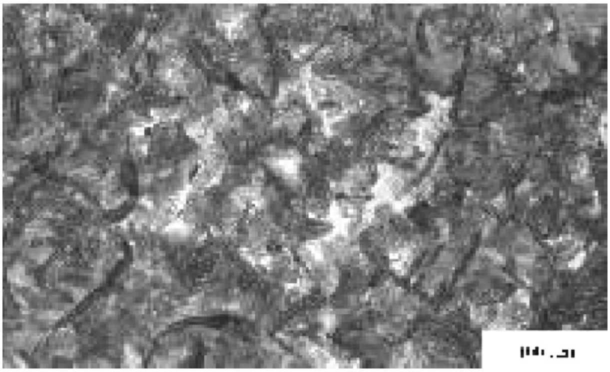

Figure 1-7-1 Gray cast iron, Fe 3.2% C and Si 2.5% by wt, containing graphite flakes in a matrix, which is pearlitic. The speckled white regions represent a phosphide eutectic. Picture courtesy of Bombay Malleable, Andheri-Kurla Road, Bombay (1983).

The fluidity of the molten iron is affected by the mold condition’s pouring rate, and amount of superheat above freezing (liquidus) temperature. It may be noted that as the total carbon (TC) decreases, the liquidus temperature increases and the fluidity at a given pouring temperature also decreases.

Chilled cast iron

When a localized area of gray cast iron is cooled very rapidly from the melt, cast iron is formed at the place that has been cooled. This type of white cast iron is called chilled cast iron. A chilled iron casting can be produced by adjusting the carbon composition of the white cast iron, so that the normal cooling rate at the surface is just fast enough to produce white cast iron, whereas the slower cooling rate below the surface will produce gray iron. The depth of chill decreases, and the hardness of the chilled zone increases with increasing carbon content.

Chromium in small amounts is often used to control chill depth, because of the formation of chromium carbides. Chromium is used in amount of 1%–4% in chilled iron to increase hardness and improve abrasion resistance. It also stabilizes carbide and suppresses the formation of graphite in heavy sections. When added in amounts of 12%–35%, chromium will impart resistance to corrosion and oxidation at elevated temperatures.

Nodular (spheroidal graphite) cast iron

Nodular iron is also called ductile iron. The graphite is present as tiny balls or spheroids. Because the spheroids interrupt the matrix much less than graphite flakes, nodular cast iron has higher strength and toughness than gray cast iron. The formation of nodules or spheroids occurs when eutectic graphite separates from the molten iron during solidification. The separation of graphite in nodular form is similar to separation of graphite in gray cast iron except that the additives facilitate the graphite to take nodular shape.

Spheroidal graphite (SG) cast iron has excellent toughness; it has higher elongation and is used widely, for example, in crankshafts. Unlike malleable iron, nodular iron is produced directly from the melt and does not require heat treatment. Magnesium or cerium is added to the ladle just before casting. The matrix can be either ferrite or pearlite or austenite. The quality of SG iron is excellent, and X-ray quality castings are regularly produced.

The latest breakthrough in cast irons is where the matrix of SG cast iron is not pearlite but bainite. The chemical composition of the SG cast iron is similar to that of the gray cast iron but with 0.05 wt% of magnesium. This results in a major improvement in toughness and strength. The bainite is obtained by isothermal transformation of the austenite at temperatures below which pearlite forms. The process of graphitization is discussed in some detail in the chapter on heat treatment.

Castability, solidification, and shrinkage

The material as liquid has high fluidity and excellent castability, but it also has very high surface tension. This demands that the sand and molding equipment used must have a rigid mold of high density and capable of good heat transfer.

The formation of graphite during solidification causes an increase in volume; this is capable of countering the loss of volume due to the liquid-to-solid phase change in metallic constituents. SG iron castings typically require very few risers to work as reservoirs of the molten metal to fill the mold. Because of this property, the ratio of weight of the usable casting to the weight of the metal poured, called *mold yield*, is much higher when compared with either steel casting or malleable iron castings. Yet this advantage is not as high when compared with gray cast iron.

Casting design engineers must compensate for the shrinkages of cast iron. Shrinkages occur both during the solidification and subsequent cooling to room temperature; this is done by designing a pattern larger in size than the final produced casting. The shrinkage allowance for ductile and SG iron is 0–0.75, as compared with 1% for gray iron, and 2% for white cast iron and carbon steel castings. The shrinkage allowance for alloy steel casings is 2.5%.

Alloy cast irons

Alloy cast irons contain specially added elements to modify the physical or mechanical properties. Chromium forms complex iron-chromium carbides to increase strength, hardness, depth of chill, and resistance to wear and heat. Copper breaks up massive cementite and strengthens the matrix. Molybdenum improves mechanical properties such as fatigue strength, tensile strength, heat resistance, and hardness. Nickel is used to control the microstructure by favoring the formation of pearlite.

Corrosion, wear, abrasion, and heat resistance of alloy cast irons

These groups of alloy cast iron consist of high-silicon, high-chromium, and high-nickel cast irons. They are often used for making valves, pumps bodies, turbocharger housings, manifolds, compressor parts, and several other industrial equipments for brine and caustic service conditions.

Corrosion, wear, abrasion, and heat resistance of alloy cast irons depend principally on their chemical composition and microstructure. The dominating factors are the chemical composition and the structure of the matrix. The three distinct groups of the alloyed cast irons, which have enhanced heat and corrosion resistance for specific environments, are

1. High-Silicon Cast Irons
2. High-Chromium (Ni-Hard) Cast Irons
3. High-Nickel (Ni-Resist) Cast Irons

Heat-resistant alloy gray and ductile irons are Fe-C-Si alloys with additions of silicon (above 3%), chromium, nickel, molybdenum, or aluminum to improve their high-temperature properties.

At temperatures above 796°F (425°C), the mechanical properties of cast irons gradually decrease as the temperatures rise and the iron undergoes a chemical change during growth as well as oxidation. Growth is a permanent increase in volume that occurs at elevated temperatures in some cast irons, gray cast irons in particular. It is attributed to the expansion that accompanies the reaction of Fe_3C changing to graphite and iron; and the oxidation of the iron after graphite is oxidized away as carbon mono-oxide. Oxidation also can occur on the cast iron casting's surface after sufficient exposure to high temperatures. If the surface oxide scale is porous or flakes off at high temperatures, combined oxidation of the metal will occur. Eventually the strength of the material will decrease due to loss of the material in scaling.

Classification of special high-alloy cast irons

Graphite free

These cast irons may have carbides, martensite Bainitic, and Austenitic grain structures. These may be associated with some graphite and pearlite structures. It is common to find the details of these cast irons specified as one of the grades described in ASTM A 532. Table 1-7-1 describes a sample of typical ASTM grades for information only; more accurate and full information should be obtained from the most recent issue of the ASTM specification.

1. Pearlitic Iron	Abrasion-Resistant Cat Irons
2. Martensitic White Iron (Ni-Hard)	Wear Resistant
3. High-Chromium Iron (11%–28% Cr)	Wear, Corrosion, and Heat Resistant

Table 1-7-1 Graphite-bearing cast iron.

Ferritic	5% Si Iron	Heat Resistant
	High (15%) Silicon Iron	Corrosion Resistant as can be found in ASTM A 518, Grade 1, 2, and 3
Austenitic	18% Ni (Ni-Resist)	Corrosion and Heat Resistant as can be found in ASTM A 439
	18% Ni, 5% Si	Heat and Corrosion Resistant ASTM A 439
Acicular	High Strength	Wear Resistant

High-silicon cast irons

Standard ductile cast irons contain approximately 1.8%–2.8% silicon, whereas modified ductile cast irons typically contain 3.5% silicon. High-silicon cast iron contains silicon in the range of 14.20%–14.75%.

Silicon cast iron has excellent resistance to corrosion especially in sulfuric acid environment, in all concentrations to 100% up to the atmospheric boiling point.

The corrosion rates are normally reduced to very low levels to typically less than 5 mpy (0.13 mm/y). However if the environment contains hot acid ranging from 5% to 55% of H_2SO_4, then the corrosion rates may increase to as high as 20 mpy (0.51 mm/y).

Above 100% sulfuric acid, silicon cast iron is rapidly attacked by free SO_3. However the main limit of silicon cast iron is its susceptibility to thermal and mechanical shock. They have poor mechanical properties such as low thermal and mechanical shock resistance, are difficult to cast, and are virtually unmachineable.

In general, the principal alloying element silicon ranges between 12% and 18%. As stated earlier, the presence of silicon above 14.2% gives the material its signature property of corrosion resistance. High-silicon cast irons represent the most commonly specified corrosion-resistant alloys at moderate cost.

Chromium and molybdenum are also added in combination with silicon to develop excellent corrosion resistance targeting specific environments.

In high-silicon corrosion-resistant grades that have a silicon level exceeding 14.2%, they exhibit excellent corrosion resistance to H_2SO_4, HNO_3, HCl, CH_3COOH, and most mineral and organic acids and corrosives. These 14.2% or higher cast irons have very high resistance to boiling 30% H_2SO_4.These high-silicon corrosion-resistant grades also display good resistance to oxidizing and reducing environments, and they are least affected by acid concentration or temperature.

Exceptions to this resistance to the vast array of acidic environments are environments containing hydrofluoric acid (HF), fluoride salts, sulfurous acid (H_2SO_3), sulfite compounds, and strong alkalis and alternating acid-alkali solutions.

Other high-silicon cast irons with high-silicon content from 12%–18% become very resistant to corrosive acids. High-silicon irons with 16.5% silicon are resistant to boiling sulfuric acid and nitric acids at almost all concentrations.

Silicon contents of less than 3.5% increase the rate of growth of gray cast iron by promoting graphitization. However, silicon contents of 4%–8% greatly reduce both oxidation (scaling) and growth. Silicon increases the scaling resistance of cast iron by forming light surface oxide that is impervious to oxidizing atmospheres. Silicon also raises the ferrite-to-austenite transformation temperatures to about 1652°F (900°C), which helps to control the expansion and contraction properties up to 1652°F (900°C) due to the phase transformation.

Some of these grades are essentially differentiated by the varying degree of alloyed chromium and manganese.

High-chromium cast irons (Ni-hard)

These are essentially white cast irons alloyed with 12%–18% chromium and are popularly known in the industry as **Ni-hard**. Chromium imparts abrasion resistance and prevents oxidation. High-chromium cast irons are resistant to oxidizing acids. They are particularly resistant to nitric acid and are useful for working with weak acids under oxidizing conditions in several organic acid solutions and with salt solution.

When the chromium levels exceed 20%, high-chromium cast irons exhibit good resistance to oxidizing acids, particularly nitric acid (HNO_3). High-chromium cast irons are resistant to reducing acids. They are used in saline solutions, organic acids, and marine and industrial atmospheres. These materials exhibit excellent resistance to abrasion and, with proper alloying additions, they can also resist combinations of abrasion and liquids including some dilute acid solutions.

The mechanical properties of high-chromium cast irons are better than those of the high-silicon cast irons. The high-chromium cast irons respond to heat treatment when the carbon and chromium contents are appropriately adjusted. However, machining of these alloys is very difficult.

Chromium is added to heat-resistance cast irons because it assists in stabilizing carbides and forms a protective oxide on the metal surface. Even small additions of chromium (0.5%–2.0%) reduce growth in gray irons subjected to cyclic heating at 1470°F (800°C). After extended high-temperature service, the pearlitic matrix of as-cast 0.8% Cr heat-resistant cast irons is transformed to ferrite, and its cementite is spheroidized in structure. Higher chromium additions of 15%–35% provide excellent oxidation and growth resistance for temperatures up to 1800°F (980°C). However, these high-chromium irons have a white iron structure. Even though they have good strength properties, they also have limited machinability. The typical chemical requirements of various grades and class of alloys castings available in the market are given in Table 1-7-2.

High-nickel cast irons (Ni-resist)

These materials contain large percentage of nickel and copper and are resistant to such acids as concentrated sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4) at slightly elevated temperatures, hydrochloric acid (HCl) at room temperature, and such organic acids as acetic acid, oleic acid, and stearic acid. When nickel exceeds 18% austenitic, cast irons are mainly immune to alkali or caustics, although stress corrosion cracking (SCC) is possible.

Table 1-7-2 Typical chemical compositions of alloy castings.

Class	Type	Designation	C	Mn	Si	Ni	Cr	Mo	Cu	P	S
I	A	Ni-Cr-Hc	2.8–3.6	2.0 max	0.8 max	3.3–5.0	1.4–4.0	1.0 max	…	0.3 max	0.15 max
I	B	Ni-Cr-Lc	2.4–3.0	2.0 max	0.8 max	3.3–5.0	1.4–4.0	1.0 max	…	0.3 max	0.15 max
I	C	Ni-Cr-GB	2.5–3.7	2.0 max	0.8 max	4.0 max	1.0–2.5	1.0 max	…	0.3 max	0.15 max
I	D	Ni-HiCr	2.5–3.6	2.0 max	2.0 max	4.5–7.0	7.0–11.0	1.5 max	…	0.10 max	0.15 max
II	A	12% Cr	2.0–3.3	2.0 max	1.5 max	2.5 max	11.0–14.0	3.0 max	1.2 max	0.10 max	0.06 max
II	B	15% Cr-Mo	2.0–3.3	2.0 max	1.5 max	2.5 max	14.0–18.0	3.0 max	1.2 max	0.10 max	0.06 max
II	D	20% Cr-Mo	2.0–3.3	2.0 max	1.0–2.2	2.5 max	18.0–23.0	3.0 max	1.2 max	0.10 max	0.06 max
III	A	25% Cr	2.0–3.3	2.0 max	1.5 max	2.5 max	23.0–30.0	3.0 max	1.2 max	0.10 max	0.06 max

High-nickel cast irons are widely used and are generally known as Ni-Resist cast irons. Austenitic gray cast irons contain 14%–30% nickel and are resistant to a mildly oxidizing acid environment. They are also resistant to sulfuric acid at room temperature. As compared with unalloyed cast irons, high-nickel cast iron is most resistant to alkalis.

Ni-Resist is particularly useful for high-temperature service. Because of their austenitic matrix and with flake graphite, the high-nickel cast irons are the toughest of all cast irons. The flake graphite also gives them excellent machinability and good foundry properties, although this gives them lower tensile strengths. In contrast, the high-nickel ductile irons have higher strength and ductility because they have nodular graphite.

Austenitic cast irons containing 18% or more nickel, up to 7% copper, and 1.75%–4% carbon are used for applications where both heat and corrosion resistance is required. The Ni-Resist cast irons have good resistance to high-temperature scaling and growth up to 1500°F (815°C) for most oxidizing atmospheres. In sulfur-containing atmospheres, however, the nickel content of these alloys limits their use to temperatures below 932°F (500°C).

The austenitic nickel cast irons have considerably greater toughness and shock resistance than other heat-resistant silicon and chromium alloy irons. The high -nickel cast irons with nodular graphite microstructure are considerably stronger and have higher ductility than the flaked graphite nickel alloy irons.

Austenitic gray cast irons

The austenitic gray iron castings are primarily used for their resistance to heat, corrosion, and wear. Austenitic gray iron is characterized by uniformly distributed graphite flakes and some carbide. They are noted for the presence of sufficient alloy content to produce an austenitic structure.

These castings are produced by melting in different types of foundry furnaces that may include any of the following:

- Cupolas furnace
- Air furnaces
- Electric arc or induction furnaces
- Crucible furnaces, etc.

The foundry practices include testing and chemical analysis to establish that the following elements are in the casting to the limits specified:

- Carbon
- Silicon
- Manganese
- Nickel
- Copper
- Chromium
- Sulfur
- Molybdenum

Table 1-7-3 Typical mechanical properties of austenitic gray cast irons.

Casting type specification	Type	Tensile strength (min) ksi	Hardness (min) (BHN)
Ni-Resist	1	25	131
Ni-Resist	1B	30	149
Ni-Resist	2	25	118
Ni-Resist	2B	30	171
Ni-Resist	3	25	118

Mechanical properties including hardness checks are also checked and verified to the specified values. Other quality control includes the verification of magnetic permeability of the castings. These castings are not necessarily nonmagnetic unless specific requirements are specified.

There are several types and grades of casing under this group; the best way to know them is to reference the most recent ASTM specifications The list given here and in Table 1-7-3 are some of the types and grades and their properties:

- Type 1
- Type 1b
- Type 2
- Type 2b
- Type 3
- Type 4
- Type 5
- Type 6

The austenitic ductile iron castings are used primarily for their resistance to heat, corrosion, and wear, and for other special purposes. The castings are produced using a melt process in any of the furnaces including cupola furnace, air furnace, electric furnace, or a crucible furnace.

Austenitic ductile iron, also known as austenitic nodular iron or austenitic spheroidal iron, is characterized by having its graphite substantially in a spheroidal form and substantially free of flake graphite. It contains some carbides and sufficient alloy content to produce an austenitic structure.

The iron castings are checked for magnetic permeability. The casting samples are analyzed for the conformance to the specified required chemical compositions for following elements:

- Carbon
- Silicon
- Manganese
- Phosphorus
- Nickel
- Chromium

Table 1-7-4 Austenitic ductile iron.

Specification	Type	Tensile strength (min) ksi	Hardness (min) (BHN)
Ni-Resist	D-2	58	139–202
Ni-Resist	D-3	55	139–202
Ni-Resist	D-3A	55	131–193

Mechanical test is conducted to establish that the cast iron meets the required tensile strength, yield strength, elongation and hardness values. Table 1-7-4 shows the typical tensile vales and hardness of austenitic ductile cast irons. Hardness is often reported in Brinell numbers.

Steel castings

Although cast irons as discussed in this chapter are not steel, there is another class of engineering material that is often confused as cast iron by some engineers. They are cast, but they are not cast iron. This class is, in fact, steel cast in engineering shapes and forms.

Steel production can be in various forms; apart from primary steel production, steel is converted into various forms through various secondary processes.

These secondary processes may include forms produced by rolling, extrusions or forgings, and castings. Plate sheets are the forms of steel in rolled condition; seamless pipes and tubes are examples of extrusion; forges billets, sections, and more user-identifiable forms like flanges and some valves, and fittings are examples of the forging processes. Larger and intricate components like valve bodies, pumps, etc. are often produced by steel casting, a process similar to that of cast iron casting, but the raw material is not a cast iron but steel.

There are as many varieties and grades of cast steel as there are steel grades. Most of these steel grades are castable, but there are some that are not easy to cast. Most cast steels have very different identification systems, and this has created a number of grades. Added to that is the fact that various bodies use their own identification process.

The importance of cast steel to a welding engineer can never be overemphasized. These steels are a bulk of steel that are welded, repaired, and heat-treated as they are used in the construction of various components. The following is a brief discussion and introduction to cast steels.

The steel castings are generally ordered as ASTM grades and per ASTM requirements, although other specifications are also used and specified.

The following are some of the frequently specified steel casting specifications that define and cover different grades of castings for various uses. Several of the common requirements for most of the castings are described in the following.

ASTM A 781/A 781M: Castings, steel and alloy, common requirements for general industrial use

This specification covers a group of requirements that are mandatory requirements of the following ASTM steel casting specifications:

- ASTM A 27/A 27M
- ASTM A 128/A 128M
- ASTM A 148/A 148M
- ASTM A 297/A 297M, A
- ASTM 447/A 447M
- ASTM MA 486/A 486M
- ASTM A 494/A 494M
- ASTM A 560/A 560M
- ASTM A 743/A 743M
- ASTM A744/A 744M
- ASTM A 747/A 747M
- ASTM A 890/A 890M
- ASTM A 915/A 915M
- ASTM A 958

ASTM A 703/A 703M: Steel castings, general requirements for pressure containing parts

This specification covers a group of common requirements that, unless otherwise specified in an individual specification, shall apply to steel castings for pressure-containing parts under each of the following ASTM specifications:

- ASTM A 216/A 216M
- ASTM A 217/A 217M
- ASTM A 351/A 351M
- ASTM A 352/A 352M
- ASTM A 389/A 389M
- ASTM A 487/A 487M
- ASTM A 985, A 990
- ASTM A 995

ASTM A 957: Investment castings, steel and alloy, common requirements for general industrial use

This specification covers a group of requirements that are mandatory for castings produced by the investment casting process to meet the metallurgical requirements of the following:

- ASTM A 27/A 27M
- ASTM A 148/A 148M
- ASTM A 297/A 297M
- ASTM A 447/A 447M

- ASTM A 494/A 494M
- ASTM A 560/A 560M
- ASTM A 732/A 732M
- ASTM A 743/A 743M
- ASTM A 744/A 744M
- ASTM A 747/A 747M
- ASTM A 890/A 890M
- ASTM A 915/A 915M

ASTM A 985: Steel investment castings—General requirements for pressure-containing parts

This specification covers a group of common requirements, which are mandatory for steel castings produced by the investment casting process for pressure-containing parts under each of the following ASTM specifications:

- ASTM A 216/A 216M
- ASTM A 217/A 217M
- ASTM A 351/A 351M
- ASTM A 352/A 352M
- ASTM A 389/A 389M
- ASTM A 487/A 487M

ISO 4990: Steel castings—General technical delivery requirements

This international specification is about the general technical delivery requirements for the supply of steel, nickel, and cobalt alloy castings, including the requirements for the selection and preparation of samples and test pieces.

Stainless steels and other CRAs

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Stainless steels are iron base alloys that contain a minimum of approximately 11% chromium (Cr). This is an important number needed to create a passivating layer of chromium-rich oxide to prevent rusting on the surface. Several stainless steel grades are produced to address specific demands of the environment that they are expected to protect; for this purpose, other elements are also added to the steel. Nickel, copper, titanium, aluminum, silicon, molybdenum, niobium, nitrogen, sulfur, and selenium are some of the commonly used elements that are alloyed to impart the required properties to the specific steel grade. The corrosion resistance and corrosion properties of stainless steel are briefly discussed in this chapter. Readers desirous of more in-depth knowledge about these topics are guided to the book *Corrosion and Corrosion Prevention* by the same author.

Stainless steel production

The process of stainless steel production involves a series of processes. First, in an electric arc furnace (EAF) the steel is melted, and alloying elements like chromium, silicon, nickel, etc. are added and melted in intense heat. Usually this process continues for about 8–12 h. This is followed by casting the molten metal into one of several shapes. These shapes may include blooms-rectangular shapes, billets-round or square shapes of 1.5 in., or slabs, rods, and tubes.

Forming

The semifinished steel goes through forming operations, beginning with hot rolling, in which the steel is heated and passed through a series of rolls where the blooms and billets are formed into bar and wire.

- Bars are available in all grades and come in rounds, squares, octagons, or hexagons of 0.25 in. (6 mm) in size.
- Wire is usually available up to 0.5 in. (13 mm) in diameter or size.
- The slabs are formed into plate, strip, and sheet.
- Plate is defined as rectangular shapes of more than 0.1875 in. (5 mm) thick and more than 10 in. (250 mm) wide.
- Strip is defined as rectangular shapes of less than 0.185 in. (5 mm) thick and less than 24 in. (610 mm) wide.
- Sheet is defined as rectangular shapes of less than 0.1875 (5 mm) thick and more than 24 (610 mm) wide.

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Heat treatment

Once the final shape is formed, most types of stainless steel must go through an annealing process. Annealing is a heat treatment in which the steel is heated and cooled under controlled conditions to relieve internal stresses and soften the metal. Some steels are heat-treated for higher strength. However, such a heat treatment, known as age hardening, requires careful control, because even small changes from the recommended temperature, time, or cooling rate can seriously affect the end properties. Lower aging temperatures produce high strength with low fracture toughness, whereas higher-temperature aging produces a lower strength, tougher material.

Although the rate of heating to reach the aging temperature of 900–1000°F (482–537°C) does not affect the properties, the control on cooling rate is very important as it does affect the properties if not controlled. A postaging quenching treatment is often carried out to increase the toughness of the steel. One such process involves water quenching in which the material is quenched in an ice-water bath of about 1.6°C (35°F) for 2 h.

Different type of steels such as austenitic, ferritic, or martensitic receive different heat treatments. Austenitic steels are heated to above 1037°C (1900°F) for a time depending on the thickness. Thick sections are quenched in water and thinner sections are either cooled by air-cooling or air-blasting. Rate of cooling is of importance; if cooled too slow, carbide precipitation can occur.

The carbide precipitation can be eliminated by thermal stabilization. In this method, the steel is held at 815–870°C (1500–1600°F) for several hours.

Descaling. eat treatment causes a scale to build up on the surface of the steel. The scale is removed by several methods.

Pickling is done to remove scale. The material is immersed in a bath of nitric-hydrofluoric acid, and the acid leaches out the scale from the surface.

Electrocleaning is also carried out to descale the steel. The process involves application of an electric current to the surface using a cathode and phosphoric acid.

The annealing and descaling are carried out at different stages depending on the type of steel being made. For example, bar and wire go through further forming steps (more hot rolling, forging, or extruding) after the initial hot rolling before being annealed and descaled. Sheet and strip, on the other hand, go through an initial annealing and descaling step immediately after hot rolling. After cold rolling (passing through rolls at a relatively low temperature), which produces a further reduction in thickness, sheet and strip are annealed and descaled again. A final cold-rolling step prepares the steel for final processing.

Cutting stainless steel

A cutting operation is usually necessary to obtain the desired blank shape or size. This is done to trim the part to its final size. Mechanical cutting is accomplished by a variety of methods, including straight shearing by guillotine knives, circle shearing by circular knives horizontally and vertically positioned, blanking by metal punches, and dies to punch out the shape by shearing. Nibbling is a process used for cutting by blanking out a series of overlapping holes and is ideally suited for irregular shapes; only some stainless steels can be saw-cut by high-speed steel blades.

Some stainless steel can also be cut using flame cutting, which involves a flame-fired torch using oxygen and propane in conjunction with iron powder. This method is clean and fast.

Another cutting method that is used is plasma jet cutting. To make a cut, this process uses an ionized gas column in conjunction with an electric arc passing through a small orifice. The force of the gas and high heat generated by the gas plasma melts the metal and makes the cut.

Finishing

Surface finish is an important requirement for stainless steel products, depending on the end application. The surface finish is a very important property to specify.

The main reasons to consider when specifying the surface finish could include one or all of the following:

1. The appearance.
2. Process convenience.
3. Corrosion protection.
4. To facilitate lubrication; often a rougher surface is specified.
5. Surface condition specific to facilitate further manufacturing steps.

Fabrication of stainless steel

After the stainless steel in its various forms are packed and shipped to the fabricator or end user, a variety of secondary processes are needed to make it useful for a specific service. Further shaping is accomplished using a variety of secondary processing that may include rolling forming, press forming, forging, press drawing, extrusion, welding cutting, additional heat treating, machining, and cleaning processes.

Welding and joining

The details of welding stainless steel are discussed in Section 2 of this book; however, a brief introduction is included here.

There are a variety of methods for joining stainless steel; welding is the most common. Several variations of fusion and resistance welding processes can be used. In fusion welding, heat is provided by an electric arc struck between an electrode and the metal to be welded. In resistance welding, bonding is the result of heat and pressure. Heat is produced by the resistance to the flow of electric current through the parts to be welded, and pressure is applied by the electrodes. After the parts are welded together, they must be cleaned around the joined area.

Types of stainless steels

Stainless steels are used for both corrosion and high-temperature resistance applications. A three-number system as listed here is used to identify stainless steels. In the following list, the three-digit number generally corresponds with the type and group of alloying elements. The first digit is the group identifier, and the last two digits identify the specific type of alloy.

- 2xx Chromium-nickel-manganese
  Nonhardenable, austenitic, nonmagnetic
- 3xx Chromium-nickel
  Nonhardenable, austenitic, nonmagnetic
- 4xx Chromium
  Hardenable, martensitic, magnetic
- 4xx Chromium
  Nonhardenable, ferritic, magnetic
- 5xx Chromium
  Low chromium, heat-resisting

The corrosion resistance in stainless steel is obtained by the presence of a thin, adherent, stable chromium oxide or nickel oxide film that protects the steel. A minimum of 10% Cr is required to develop this tenaciously adhering, uniformly developed oxide film.

Classification of stainless steel

Stainless steels are classified into five families. Four of these are based on their crystallographic structures: martensitic, ferritic, austenitic, and austenitic plus ferritic (called duplex). The fifth class is based on the type of heat treatment used to produce certain properties, and these are called precipitation-hardenable alloys, or PH steels. Each of these are discussed further in the text.

Martensitic stainless steels

These are essentially Fe-Cr-C alloys that have body-centered tetragonal (bct) crystalline structure, which is martensite in a hardened condition. These steels are ferromagnetic; they can be hardened by heat treatment. These steels can resist corrosion in mild environments. The addition of a small amount of nickel improves corrosion resistance properties. Typically, these steels contain steels 11.5%–18% chromium and up to 1.2% carbon. The chromium-to-carbon ratio is balanced to maintain martensitic structure. Examples of this group of steel are Types 403, 410, 420, and 501.

Other elements like vanadium, silicon, tungsten, and niobium are also added to induce tempering after hardening. The alloying is in a very limited scale to maintain the martensitic structure.

Properties of martensitic stainless steel

In annealed condition, these steels exhibit good tensile properties. Generally, these steels have a yield strength of approximately 275 MPa (40 ksi). Steel responds to cold work by a moderate increase in hardness. In annealed condition, these alloys have good toughness and ductility, which decreases as hardness is increased by heat treatment. Heat treatment hardening and tempering increases yield strength up to 1900 MPa (275 ksi). Typically, the hardness values range from 150 HB in annealed condition to 600 HB in fully hardened condition.

Martensitic stainless steels are magnetic and can be easily cold-worked and machined. In annealed condition, they have good toughness, moderate corrosion resistance, and are easily hot-worked. They are most corrosion resistant when properly heat-treated. Because of the high alloy content, these steels undergo sluggish transformations and results in high hardenability. Maximum hardness can be achieved by air-cooling. Type 416 steels contain a small amount of sulfur to improve machinability, which also reduces corrosion resistance.

Ferritic stainless steels

These are straight iron-chromium alloys that contain chromium in the rage of 14%–27%. Examples of this group of steel are Type 405 and Type 430 steel. This type of steel has bcc structure. To obtain specific properties, some grades are alloyed with molybdenum, aluminum, silicon, titanium, and niobium.

These steels are ferromagnetic, possess good ductility, and are relatively easy to work with. Carbon percentage for these steels range from 0.02% to 0.2%. Due to the low carbon content, hardenability cannot be increased by heat treatment and can be only moderately hardened by cold-working. Cold work also strengthens the material and reduces its ductility. In comparison, these steels in the annealed condition have about 1.5 times more strength than that of carbon steel. In annealed condition, they have the best resistance to corrosion. Prolonged exposure of these steels to the temperature range of 400–510°C (750–950°F) can cause brittleness and loss of notch-impact strength.

Properties of ferritic stainless steel

In annealed state, the yield strength of typical ferritic stainless steel is in the range of 240–380 MPa (35–55 ksi) especially alloy grades like Type 444, UNS S 44660, and S 44627. These specially alloyed steels, also called superferritic stainless steels, have good resistance to corrosion and are especially good for resistance to stress corrosion cracking (SCC) and pitting.

Pitting resistance equivalent

Most of these alloys are developed to serve in a specific type of environment, and resistance to corrosion is one of their properties. The resistance to general corrosion of these steels is addressed by alloying elements that develop passivating layers of metallic oxide. However, localized corrosion is not easy to predict hence not easy to control. The ability to assess the resistance to pitting of an alloy is determined by a calculated value called Pitting resistance equivalent (PRE) number.

These alloys exhibit some degree of pitting resistance, which is calculated by a weighted average of key elements like chromium, molybdenum, and nitrogen, as is given in the following equation. A higher PRE number is an indicator of better resistance to pitting, and such alloys are preferred where localized corrosion in the form of pitting may be of specific concern.

$$\mathrm{PRE} = \%\mathrm{Cr} + 3.3\,(\%\mathrm{Mo}) + 16\,(\%\mathrm{N})$$

It may be noted that the elements include nitrogen, which is a gas, as it has significant influence on pitting resistance property of an alloy.

Austenitic stainless steels

We have discussed basics of stainless steel in the chapter dealing with production of steel. This group of steel is by far the largest group of stainless steel. These steels contain chromium (Cr) in the range of 16%–26% and nickel (Ni) in the range of 3.55% (grade 201) to 37% (grade 330); other alloying elements include carbon ranging from 0.03% to 0.25%. Molybdenum, niobium, titanium, and tantalum are specialty additions to improve specific properties like stabilizing or for marine services etc. Other regular alloying elements include manganese, silicon, sulfur, and phosphorous.

Stainless steels are nonmagnetic and can be hardened by cold-working. However, they cannot be hardened by heat treatment. They have excellent low temperature ductility. Some grades like grade 310 are equally good for moderate to high temperature services.

The chromium-nickel (Type 3xx) and chromium-nickel-manganese (Type 2xx) stainless steels are the two major groups. They can be hot-worked and cold-worked, but they do readily work harden. Austenitic stainless steels are extremely shock-resistant and are not easy to machine.

They exhibit the best high-temperature strength and scaling resistance, and superior corrosion resistance compared with the ferritic and martensitic stainless steels. Type 302 is a basic alloy that has been modified to more than 20 basic alloys.

Properties of austenitic stainless steel

The strength of austenitic stainless steel is very much comparable to mild carbon steel; its typical yield strength is between 200 and 275 MPa (30–40 ksi), and the elongation is measured in the range of 40%–60%. Grade 200 series of steel have better yield strength in annealed conditions, 345–482 MPa (about 50–70 ksi).

The corrosion resistance of these steels is excellent in most environments. Of the 3xx series stainless steel, basic grade 304 is commonly used in food, dairy, and beverage industry. They are also good in an oxidizing environment; the stabilized form of basic Grade-304 and renumbered as Grade 321 (titanium-stabilized) and 347 (niobium-stabilized) can resist thermally induced embrittlement.

Grade 310 with higher chromium and carbon level is suitable for higher temperature services; similarly Grade 316 is alloyed with molybdenum to impart resistance from a marine environment.

Duplex stainless steels

The Fe-Cr-Ni system alloys have two phases. They typically contain 20%–30% chromium and 5%–8% nickel. The alloy system is called *duplex* because it typically contains approximately 50/50 austenitic and ferritic phase in its microstructure. These steels contain low carbon, and molybdenum, tungsten, copper, and nitrogen are added as alloying elements.

Various grades of Duplex stainless steels have been developed, and they are often classified as lean duplex, standard duplex steel, super duplex steels, or even as hyperduplex steels. All these alloys have been developed to address demand, specific care, and procedure for welding and fabrication. Specific treatments are required to maintain the ratio of ferrite and austenitic structure specific to each alloy.

Often described by alloys with UNS numbers such as UNS s32505, UNS s23707, UNS s31803, UNS s32750, s32760, s32520 etc., they all are unique with their chemical composition and microstructure, and in their properties to resistance to corrosion with various degree of corrosion resistance and/or specific properties to resist specific corrosion. The UNS numbering system indicates the nominal percentages of principle alloying elements.

Standard duplex steels such as UNS s31803 and s32205 are described as duplex stainless steels with a microstructure of 50:50 austenite and ferrite. The steel combines good mechanical strength (typically up to more than 480 MPa yield strength) and ductility with moderate to good corrosion resistance in a variety of environments.

UNS 23707 is a hyperduplex stainless steel containing 27% chromium, 6.5% nickel, 5% molybdenum, 0.03% carbon, and 0.4% nitrogen. The alloy has nominal PRE of 49. (PRE is described elsewhere in this chapter and is an indicator of resistance to pitting.) This specific alloy was developed for service in environments that have severe chloride corrosion possibilities.

See Tables 2-7-2 and 2-7-3 and associated text in welding sections of the book for more about the numbering system, chemical composition, and mechanical properties and welding of these alloys.

Properties of duplex stainless steel

The yield strength of these steels range from 550 to 690 MPa (80–100 ksi).

The alloy, due to its ferritic structure, is susceptible to loss of mechanical strength, which leads to embrittlement at elevated temperatures. Prolonged service at and above 300°C (570°F) is not advised.

The greatest advantage of duplex stainless steel is the resistance to corrosion, especially to pitting corrosion. The alloys exhibit PRE from 22 (UNS s32304) to 47 (UNS s32750).

Precipitation-hardening stainless steels

Precipitation hardening is defined as caused by the precipitation of a constituent from a supersaturated solid solution. Artificial aging of a metal is carried out in which a constituent precipitates from the supersaturated solid solution. This chromium-nickel grade of steel is hardened by an aging treatment.

These grades were developed during World War II. They are usually supplied in a solution-annealed condition and are aged for strength following forming. The main grades are 17-4 PH or 17-7 PH, and the classifications are based on their solution-annealed microstructure. In annealed condition, these grades are semiaustenitic steels; upon heat treatment, the microstructure is changed to martensite. Cold work enhances the aging effect, and certain alloying elements like aluminum, niobium, titanium, or copper are added to facilitate aging. ASTM A 286 is the standard to find various grades of precipitation-hardened steels. Some alloys in this class are listed here with their UNS numbers.

UNS number	Alloy type
S13800	PH13-8Mo
S15500	15-5 PH
S17400	17-4 PH
S45500	Custom 455

The 17-4 PH is solution-treated and air-cooled to allow the austenite-to-martensite transformation. Reheating is performed to increase the strength and corrosion resistance.

Properties of precipitation-hardening stainless steel

PH alloys can achieve high strength, ranging from 690 to 1700 MPa (100–250 ksi).

Grade PH 15-7 Mo(h) (UNS S15700) has yield strength of 1590 MPa (230 ksi) and corresponding hardness of more than 46 HRC, but the elongation, which is a measure of ductility, ranges from 1% to 15%, which is seriously low in all PH alloys. The corrosion resistance of these alloys is, at best, moderate.

Nonferrous materials

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Copper and copper alloys

Copper is used for its high electrical and thermal conductivity, good corrosion resistance, machinability, strength, and ease of fabrication. It can be welded, brazed, or soldered. Copper used for electrical conductors contain more than 99.9% Cu and are identified as either electrolytic tough-pitch copper (ETP) or oxygen-free high-conductivity copper (OFHC). Most copper alloys are homogeneous single-phase alloys and are not susceptible to heat treatment. Strength is increased by alloying or cold-working.

Brasses are alloys of copper and zinc. The composition may be further alloyed with lead, tin, or aluminum. Alpha (α) brass contains up to 36% Zn and has good corrosion resistance. Yellow α brasses contain 20%–36% Zn and have high ductility and strength. They are susceptible to dezincification and stress corrosion cracking. Red brasses contain 5%–20% Zn and have better corrosion resistance than yellow brasses.

Alpha plus beta brasses contain 54%–62% copper and have two phases. Muntz metal is the most widely used because it has high strength and good hot-working properties.

Bronze includes any copper alloy without zinc. Copper alloyed with tin, silicon, aluminum, and beryllium are common bronze alloys.

Cupronickel alloys contain up to 30% nickel and are always single-phase alloys. They have high corrosion fatigue resistance. These alloys are also excellent in resistance to seawater corrosion.

Aluminum and aluminum alloys

Aluminum is a nonferromagnetic, nonpyrophoric, and nontoxic material. Aluminum's density is 2.7 g/cm^3, which is about one-third of steel's density. Many aluminum alloys have better strength-to-weight ratios. Aluminum has good malleability and formability, high corrosion resistance, high electrical and thermal conductivity, and is nonsparking. Pure aluminum's tensile strength is about 90 MPa (13,000 psi), and it can be alloyed and heat-treated to increase the strength up to 690 MPa (100,000 psi). These advantageous properties have made aluminum an important engineering material, and its use has significantly changed several of the engineering machines and equipment that we use and depend on. Aluminum is not naturally available; in nature, it is found in its oxide form (Al_2O_3) commonly called alumina. The extraction process is briefly described in the following.

Aluminum is extracted by a smelting process from ore bauxite by Hall-Heroult process involving electrolyzing of the bath to extract alumina. The bauxite is dissolved in a cryolite bath with fluoride salts added to control the temperature of the bath.

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As the electrical current is passed through the bath, electrolyzing the dissolved alumina as oxygen is formed, which reacts with the carbon anode, and aluminum as metal collects at the cathode. The metal is periodically siphoned out to crucibles and subsequently cast into ingots. Aluminum recovered by this method is often referred to as primary aluminum. Secondary aluminum refers to aluminum recovered from scrap. The ingots are further processed and refined to meet industrial demands. Plates, sheets, foils, and extruded shapes and tubes are some of the products.

Physical metallurgy of aluminum

The physics of aluminum is defined by heat treatment, work hardening, and the effect of alloying elements. Heat treatment and work hardening are the two primary methods used to increase the strength of pure aluminum to make it an engineering material with strength.

- In the first category is the process applied to the nonheat-treatable alloys. This involves the dispersal of second-phase constituents in solid solution and cold-working the alloy.
- The second method is used with heat-treatable alloys, to disperse the alloying elements into a solid solution and precipitate them as coherent submicroscopic particles.

These can be further studied in detail by reviewing various phase diagrams of different alloys.

Effect of alloying elements on aluminum

Aluminum alloys contain iron silicon and another two or more elements to enhance properties. The phase formed and the function is described here.

Effect of iron

Iron is present in all aluminum as an impurity, generally left over from the smelting process of bauxite. The maximum solubility of iron in aluminum is 0.05%. During solidification of an iron-aluminum alloy, most of the iron remains in liquid phase until a eutectic of solid solution plus Al_3Fe intermetallic constituent particles that has a monoclinic crystal structure freezes. Depending on the presence of other alloying elements such as manganese, constituent particles of the metastable orthorhombic Al_6Fe phase can form instead of the Al_3Fe.

Effect of silicon

Silicon is also present as impurity. Two ternary phases, cubic $\alpha Al_{12}Fe_3Si$ and monoclinic $\beta Al_9Fe_2Si_2$, are formed by eutectic reaction. At low-silicon content level, almost all the iron is present in Al_3Fe phase. As the silicon level is increased, the α Al-Fe-Si phase appears followed by the β Al-Fe-Si phase.

In larger amounts, alloyed silicon improves castability and fluidity of the alloy. It is a preferred alloy for brazing sheets. The casting alloys contain silicon in the range of 5%–20%. Silicon along with manganese allows for precipitation hardening, and this is the basis for 6xxx type of aluminum alloy.

Effect of manganese

Manganese imparts excellent formability to the alloy. During the solidification, some of the manganese (Mn) forms $Al_6(Mn, Fe)$ and cubic $Al_{12}(Mn, Fe)Si$ by eutectic reaction. The remaining Mn remains in the solution and is precipitated during the ingot preheat as $Al_{12}(Mn, Fe)Si$ and $Al_6(Mn, Fe)$ dispersoid. These dispersoids strengthen the alloy and control recrystallized grain size. The Al-Cu-Mn alloy precipitates as $Al_{20}Cu_2Mn_3$ dispersoid particles. The effect of these on the strength is minimal, but they are helpful in controlling grain size during the solution heat treatment. The 3xxx types of alloys are example of Al-Mn alloys.

Effect of magnesium

The phase diagram of aluminum-magnesium alloy system (AL Mg) indicates a positively sloping solvus, which is a necessary condition for a precipitation hardening system. The difficulty associated with the nucleation of face-centered cubic (fcc) Al_3Mg_2 precipitates has prevented the commercialization of heat-treatable Al + Mg alloy.

Class 5xxx wrought and cast alloys are based on this system. They have excellent strength and corrosion resistance, achieved by solid solution strengthening and work hardening.

Effect of copper

During solidification, some copper chemically combines with aluminum and iron to form either tetragonal Al_7Cu_2Fe or orthorhombic $\alpha(Al,Cu,Fe)$ constituent particles. The subsequent heat treatment cannot dissolve these phases but can transform from one to another.

The aluminum and copper alloys containing magnesium (Mg) results in formation of Al_2CuMg phase by eutectic decomposition. Metastable precursor to face-centered orthorhombic Al_2CuMg precipitate strengthen the alloy. Wrought and cast 2xxx alloys area result of this phase, and these alloys are desired by the aerospace industry for their strength, fracture toughness, and resistance to crack growth.

Effect of zinc

Aluminum and zinc do not offer much strengthening to alloys, but aluminum, zinc, and magnesium precipitates provide two phases that give them strength.

Depending on the zinc/magnesium ratio, the two phases, hexagonal $MgZn_2$ and bcc $Al_2Mg_3Zn_3$, can form by eutectic decomposition in Al Zn Mg alloys. The copper-free alloys are strengthened by metastable precursor to either $MgZn_2$ or $Al_2Mg_3Zn_3$.

In alloys with copper, copper and aluminum replace Zn in $MgZn_2$ to form Mg(Zn, Cu, Al)$_2$. Al_2CuMg particles can also form in these alloys by eutectic decomposition of solid-state precipitation.

Wrought and cast alloys of 7xxx group are a result of this alloy system.

Effect of chromium

The solubility of chromium can be reduced to such an extent that primary particles (Al_7Cr) can form by peritectic reaction. The primary particles are harmful to the ductility fracture toughness and fatigue strength of the material. The acceptable upper limit of chromium is dependent on the amount of other elements in the system. Chromium dispersoids contribute to the strength in nonheat-treatable alloy (of 5xxx) system that has fcc structure in $Al_{18}Mg_3Cr_2$ dispersoids. However, the alloys that can be heat treated (e.g., 7xxx) have composition of the dispersoids $Al_{12}Mg_2Cr$.

Effect of zirconium

This element forms a peritectic with aluminum. The equilibrium Al_3Zr phase is tetragonal, but fine dispersoids of metastable cubic form during preheating treatment of the ingot. Most of the 5xxx, 6xxx, and 7xxx alloys have some amounts of zirconium (Zr), usually less than 0.15% to form Al_3Zr dispersoid for recrystallization control.

Effect of lithium

This costly element is alloyed mainly for alloys used in space industry. It reduces the density and increases the modulus of aluminum alloys. In a binary alloy, it forms Al_3Li precipitate and combines with aluminum and copper in Al-Cu-Li alloy to form a large number of Al-Cu-Al phases.

Age-hardenable alloys

Following is the list of age-hardenable aluminum alloys, with various combinations of alloying elements:

Wrought alloys,
Aluminum and copper (Al-Cu),
Aluminum, copper, and magnesium (Al-Cu-Mg),
Aluminum magnesium, and silicon (Al-Mg-Si),
Aluminum, zinc, and magnesium (Al-Zn-Mg),
Aluminum, zinc, magnesium, and copper (Al-Zn-Mg-Cu).

Casting alloys such as:

Aluminum and silicon (Al-Si).
Aluminum, silicon, and copper (Al-Si-Cu).

Work-hardenable alloys such as:

Aluminum and magnesium (Al-Mg).
Aluminum manganese (Al-Mn).

To impart additional properties to aluminum and its alloys, several heat treatment and work-hardening processes are used. Sometimes a combination of both heat treatment and work-hardening method is used.

Temper designations that are used to identify the heat treatment condition of aluminum alloys are listed here:

F = As fabricated.
O = Annealed and recrystallized.
H = Strain-hardened.
W = Solution heat-treated.
T = Thermally treated.

Aluminum alloy designations indicate the alloy group, modifications, and heat treatment where applicable. Unalloyed pure aluminum is classified as 1xxx, primarily used in electrical and chemical industries.

Other aluminum alloy groups are listed here:

1. Aluminum-copper alloys (2xxx Series) are age-hardenable and include some of the highest strength aluminum alloys such as Alloy 2024. With yield strength as high as 66 ksi (455 MPa), its engineering importance is realized by the aircraft industry.
2. Aluminum-manganese alloys (3xxx Series) are not heat treatable, have good formability, good corrosion resistance, good weldability, and are useful for architectural and general purpose applications.
3. Aluminum-silicon alloys (4xxx Series) are not heat treatable and have excellent castability and corrosion resistance. They are used primarily for making welding and brazing consumables.
4. Aluminum-magnesium alloys (5xxx Series) are not heat treatable and have good weldability, corrosion, resistance, and moderate strength. They have good corrosion resistance to a marine environment, which makes it a useful material for boat hulls and other applications.
5. Aluminum-silicon-magnesium alloys (6xxx Series) are artificially aged and have excellent corrosion resistance and workability. Alloy 6061 is commonly used for structural applications.
6. Aluminum-zinc alloys (7xxx Series) develop the highest tensile strengths but are susceptible to stress corrosion cracking. Yield strength exceeding 500 MPa (73 ksi) is achievable; this material is used for high strength applications including aircraft structures.

Aluminum is available in cast and wrought form for various applications. Principal alloying elements determine the wrought and cast aluminum designation system as discussed earlier. They are also designated based on the temper for both cast and wrought forms. Basic designations are similar to the ones discussed before. The designations are repeated here:

F As fabricated.
O Annealed.
H Strained hardened.
W Solution annealed.
T Solution heat-treated.

The system designation of T is further expanded to include different levels of heat treatment starting from T1 to T6.

Strained hardened designation is further divided into the following grades:

H1 Strained hardened only.
H2 Strained hardened and partially annealed.
H3 Strained hardened and stabilized.
H4 Strained hardened and lacquered or painted.

Nickel and nickel alloys

Nickel is noted for good corrosion resistance and is particularly effective in oxidizing environments. It forms tough, ductile solid-solution alloys with many metals. Its mechanical properties are similar to those of mild steel as it retains its strength at elevated temperatures while also maintaining ductility and toughness at low temperatures.

Nickel-copper alloys such as cupronickel have excellent corrosion resistance to a wide variety of environments and may be used at temperatures up to 815°C (1500°F).

Nickel-silicon alloys such as Hastelloy-D are strong, tough, and extremely hard. They have excellent corrosion resistance in sulfuric acid at high temperatures.

Nickel-chromium-iron alloys combine the corrosion resistance, strength, and toughness of nickel with the high temperature oxidation resistance of chromium.

Nickel-molybdenum-iron alloys such as Hastelloy-B have high corrosion resistance to hydrochloric, phosphoric, and other nonoxidizing acids.

Nickel-chromium-molybdenum-alloys such as Hastelloy-C have high corrosion resistance to oxidizing acids, good high-temperature properties, and are resistant to oxidizing and reducing atmospheres up to 1093°C (2000°F).

Titanium and titanium alloys

The elemental metal titanium has atomic number 22; as a metal, it possesses silvery lustrous properties. The density of Ti is about 0.16 lb/in.^{3} compared to steel's 0.28 lb/in.^{3}, which highlights the excellent strength-to-weight ratios of titanium alloys. The metal can be alloyed with iron, vanadium, aluminum, etc., for various industrial applications.

The metal has excellent corrosion-resistant properties. Titanium has excellent corrosion resistance up to 538°C (1000°F). Alloying elements influence the alpha to beta transition temperature and so are referred to as either alpha or beta stabilizers.

Due to the metal's high melting temperature, the metal is also used as refractory metal. The elemental titanium has two allotropic forms. The metal has low density and high ductility. The metal is paramagnetic and has low electrical and thermal conductivity.

The metal is a dimorphic allotrope; the hexagonal α-Ti changes into a body-centered cubic (bcc) lattice β-Ti forms at 882°C (1620°F). The specific heat of α-Ti increases dramatically as it is heated to this transition temperature but then falls and remains fairly constant as the β-Ti regardless of temperature.

Titanium metal and alloy surfaces oxidize immediately when they are exposed to air. Titanium readily reacts with oxygen at 1200°C (2190°F) in air and at 610°C (1130°F) in pure oxygen, forming titanium oxides. However, it is slow to react with water and air, as it forms a passive and protective oxide coating that protects it from further reaction. When it first forms, this protective layer is only 1–2 nm thick but continues to slowly grow, reaching a thickness of 25 nm in about 4 years. Materials with this property are effectively utilized in the construction of marine equipment.

Thermodynamically, titanium is a very reactive metal. The metal cannot be melted in open air because it burns before the melting point is reached. Melting is only possible in an inert atmosphere or in a vacuum, a property that must be considered if planning fabrication involving welding of titanium. Single-phase alloys are weldable and have good ductility. Some two-phase alloys are also weldable but experience loss of ductility. Two-phase alloys can be strengthened by heat treatment.

Working with metals

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Working with metals involves understanding the limits of their mechanical properties. Several aspects of these properties can be used to get the best results from the metal. There cannot be a limit of what and how much information to know about any given material. As they can be in very different environmental conditions, the impact of the environment on the metal must be studied to determine which properties of the material would be affected.

It is pertinent that a combination of knowledge, including knowledge of a material's mechanical properties and its corrosion behavior in the specific service environment, must be studied for proper selection of a material for any project. Some of the mechanical properties that have a significant impact on workability of the material are discussed in this chapter.

Elastic limit

When a material is stressed below its elastic limit, the resulting deformation or strain is temporary. Removal of an elastic stress allows the object to return to its original dimensions. When a material is stressed beyond its elastic limit, plastic or permanent deformation takes place, and it will not return to its original dimensions when the stress is removed. All shaping operations such as stamping, pressing, spinning, rolling, forging, drawing, and extruding involve plastic deformation. Pressure testing, with few exceptions, is done within the elastic limits of the material.

Plastic deformation

Plastic deformation may occur by slip, twinning, or a combination of slip and twinning. Slip occurs when a crystal is stressed in tension beyond its elastic limit. It elongates slightly, and a step appears on the surface, indicating displacement of one part of the crystal. Increasing the load will cause movement on a parallel plane, resulting in another step. Each successive elongation requires higher stress and results in the appearance of another step. Progressive increase of the load eventually causes the material to fracture.

Twinning is a movement of planes of atoms so that the lattice is divided into two symmetrical parts that are differently oriented. Deformation twins are most prevalent in close-packed hexagonal metals such as magnesium and zinc, and body-centered cubic metals such as tungsten and α-iron. Annealing twins can occur as a result of reheating previously worked face-centered cubic metals such as aluminum and copper.

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Fracture

Fracture is the separation of a body under stress into two or more parts. Brittle fracture involves rapid propagation of a crack with minimal energy absorption and plastic deformation. It occurs by cleavage along particular crystallographic planes and shows a granular appearance.

Ductile fracture occurs after considerable plastic deformation prior to failure. Fracture begins by the formation of cavities at nonmetallic inclusions. Under continued applied stress, the cavities coalesce to form a crack. This process is seen as microvoid coalescence on the fracture surface.

Polycrystalline material

Commercial materials are made up of polycrystalline grains whose crystal axes are oriented at random. Therefore, depending on their orientation to the applied stress, the deformation processes occur differently in the grains.

A fine-grained material in which the grains are randomly oriented will possess identical properties in all directions and is called isotropic.

A metal with controlled grain orientation will have directional properties (anisotropic) that may be either troublesome or advantageous, depending on the direction of loading.

When a crystal deforms, there is distortion of the lattice that increases with increasing deformation. As a result, there is an increase in resistance to further deformation, which is known as strain hardening or work hardening.

Cold-working

A material is considered to be cold-worked when its grains are in a distorted condition after plastic deformation is completed. All of the properties of a metal that are dependent on the lattice structure are affected by plastic deformation.

By cold-working, the tensile strength, yield strength, and hardness of the material is increased. Hardness increases most rapidly in the first 10% reduction by cold work and tensile strength increases linearly; conversely most of the ductility is lost due to cold-work in the first 10% reduction. Thereafter, the reduction in ductility is at much slower rate. Yield strength increases more rapidly than tensile strength. Cold-work also reduces electrical conductivity.

Stored energy

Although most of the energy used to cold-work metal is dissipated in heat, a finite amount is stored in the crystal structure as internal energy associated with the lattice defects created by the deformation. The increase in internal energy is often concentrated in the grain boundaries, resulting in localized increased susceptibility to energy-driven reactions such as corrosion.

Restoring the lattice structure of metal after cold-work—Annealing

Full annealing is the process by which the distorted cold-worked lattice structure is changed back to one that is strain-free through the application of heat. This is a solid-state process and is usually followed by slow-cooling in the furnace.

Recovery is the first stage of annealing. This is a low-temperature process and does not involve significant changes in the microstructure. The principal effect is relief of internal stresses. Recovery is a time- and temperature-dependent process. There is little change in mechanical properties, and the principal application of recovery is stress relief to prevent stress corrosion cracking or to minimize distortion produced by residual stresses.

Recrystallization occurs at higher temperatures as minute new crystals appear in the microstructure. They usually appear in the regions of highest deformation such as at grain boundaries or slip planes. Recrystallization takes place by the process of nucleation of strain-free grains and the growth of these nuclei to absorb the cold-worked material.

Recrystallization temperature refers to the approximate temperature at which a highly cold-worked material completely recrystallizes in 1 h; it may be noted that the greater the amount of deformation, the lower the recrystallization temperature. Zinc, lead, and tin have recrystallization temperatures below room temperature and so cannot be cold-worked.

Grain growth

Large grains have lower free energy than small grains because there is less grain boundary volume. Grain growth is driven by a single crystal's lowest energy state. The rigidity of the lattice opposes grain growth.

As temperature is increased, the rigidity of the lattice decreases, and the rate of grain growth is more rapid. Holding a specimen for a long time in the grain-growth temperature region (slightly below the melting point) can grow very large grains. Final recrystallized grain size is controlled by factors that influence nucleation and growth rate.

Hot-working

When a material is plastically deformed, it tends to become harder. But the rate of work hardening decreases as the working temperature is increased. Two opposing effects take place—hardening due to plastic deformation and softening due to recrystallization.

For a given material, there is a temperature at which these two effects balance. Material worked above this temperature is said to be hot-worked, and material that is worked below this temperature is said to be cold-worked. Lead and tin may be hot-worked at room temperature, whereas steel is cold-worked at 538°C (1000°F).

Hot-worked material cannot be manufactured to exact size because of the dimensional changes that take place during cooling. Cold-worked materials can be held to close tolerances but require more power for deformation and so are more expensive to produce.

Normally, by hot-working, initial reductions are carried out at an elevated temperature, and the final reductions are done cold to take advantage of both processes. The finishing temperature for hot-working determines the grain size available for further cold-working. Careful control of these processes is known as thermomechanical processing.

Mechanical properties and testing of metals

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The science of the behavior of metals and alloys subjected to applied forces is known as mechanical metallurgy.

One approach uses the strength of the material and the theories of elasticity and plasticity where a metal is considered to be a homogeneous material whose mechanical behavior is described on the basis of only a few material constants.

However, regarding the theories of strength of materials, elasticity and plasticity lose much of their power when the material's structure becomes important, and it can no longer be considered a homogeneous medium.

Strength of materials

The strength of material with respect to metallurgy is the body of knowledge dealing with the relation between internal forces, deformation, and external loads.

The material is assumed to be in equilibrium when the equations of static equilibrium are applied to the forces acting on some part of the body to obtain a relationship between the external forces and the internal forces resisting their action.

Although metals are made up of an aggregate of crystal grains having different properties in different directions, the equations of strength apply because the crystal grains are so small that the materials on a macroscopic scale are statistically homogeneous and isotropic.

Elastic and plastic behavior

All solid materials can be deformed when subjected to external load. In the previous chapter, we discussed the material's elastic and plastic deformation and their impact on formability on metals.

The recovery of the original dimensions of a deformed body when the load is removed is called elastic behavior.

The limiting load beyond which material no longer behaves elastically is the elastic limit.

A body that is permanently deformed is said to have undergone plastic deformation.

For most materials that are loaded below the elastic limit, the deformation is proportional to the load in accordance with Hooke's Law, which in simple terms says that strain is directly proportional to stress.

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Mathematically, this law can be expressed as:

$$\mathbf{F} = -kx$$

where:

1. x is the displacement of the end of the spring from its equilibrium position (in SI units: "m").
2. $\mathbf{F}$ is the restoring force exerted by the material (in SI units: "N" or "$\mathrm{kg\,m\,s^{-2}}$" or "$\mathrm{kg\,m/s^2}$").
3. k is a constant called the *rate* or *spring constant* (in SI units: "$\mathrm{N\,m^{-1}}$" or "$\mathrm{kg\,s^{-2}}$" or "$\mathrm{kg/s^2}$").

Ductile vs brittle behavior

A completely brittle metal would fracture almost at the elastic limit, and a mostly brittle material such as white cast iron would show some measure of plasticity before fracturing.

Adequate ductility is an important consideration as it allows the material to redistribute localized stresses. If localized stresses at notches and other stress concentrations do not have to be considered, it is possible to design for static situations on the basis of average stress.

With brittle materials, localized stresses continue to build up when there is no local yielding. Finally, a crack forms at one or more points of stress concentration, and it spreads rapidly over the section.

Even without a stress concentration, fracture occurs rapidly in a brittle material because the yield stress and tensile strength are nearly same.

Failure

Structural members fail in three general ways:

- Excessive elastic deformation
- Yielding or excessive plastic deformation
- Fracture

Failure due to excessive elastic deformation is controlled by the modulus of elasticity rather than the strength of the material.

Yielding, or excessive plastic deformation, occurs when the elastic limit is exceeded. Yielding rarely results in fracture of a ductile metal because the metal strain hardens as it deforms, and an increased stress is required to produce further deformation.

At elevated temperature, metals no longer exhibit strain hardening and can continuously deform at constant stress—creep.

Metals fail by fracture in three general ways:

- Sudden brittle fracture
- Fatigue fracture or progressive fracture
- Delayed fracture

A change from ductile to brittle behavior can occur when the temperature is decreased, the rate of loading is increased, and a notch forms during a complex state of stress.

Most fractures in machine parts are due to fatigue. A minute crack starts at a localized spot (notch or stress concentration) and gradually spreads over the section until it breaks. There is no visible sign of yielding at the average stresses, which are often below the tensile strength of the material.

Delayed fracture can occur as stress-rupture when fracture is on a statically loaded material at elevated temperature over a long period of time. Static loading in the presence of hydrogen can also cause delayed fracture.

Fracture

Fracture is the separation of a solid body into two or more parts under the action of stress. The fracture process has two components: crack initiation and crack propagation.

Ductile fracture is characterized by appreciable plastic deformation prior to and during crack propagation.

Brittle fracture is characterized by a rapid rate of crack propagation with no gross deformation and very little microdeformation.

For steel, the possibility of brittle fracture is increased with decreasing temperature, increasing strain rate, and triaxial stress conditions usually produced by a notch.

Different terms are used to characterize fractures:

Behavior described	**Terms used**	
Crystallographic mode	Shear	Cleavage
Appearance	Fibrous	Granular
Strain to fracture	Ductile	Brittle

Fracture control

Fracture control is a combination of measures to prevent fracture due to cracks during operation. It includes damage tolerance analysis, material selection, design improvement, and maintenance and inspection schedules.

Damage tolerance analysis has two objectives:

- To determine the effect of cracks on strength
- To determine the crack growth as a function of time

The effect of crack size on strength is diagrammed. Crack size is denoted as a length, and strength is expressed in terms of the load, P, that the structure can carry before fracture occurs.

A new structure with no defects ($a = 0$) will have a strength P_u (the ultimate design strength or load). If the maximum anticipated service load is P_s, a safety factor j is applied so that the structure can actually sustain a load jP_s.

If cracks are present, the strength is less than P_u. This remaining strength is called the residual strength P_{res}, and the diagram is called a residual strength diagram.

With a crack of size a, the residual strength is P_{res}, and a load greater than P_{res} will cause fracture to take place. The fracture process may be slow and stable at first and the structure can hang together. Eventually the fracture becomes unstable and the structure breaks. The process of stable to unstable fracture may occur in a few seconds.

At loads below P_{res}, the crack will continue to grow by other means than fracture such as fatigue, stress-corrosion, or creep.

As crack growth continues, the crack becomes longer, the residual strength lesser, the safety factor lower, and the probability of fracture higher.

The crack must not be allowed to grow so large that fracture occurs at the service load or even at P_a. The maximum permissible crack size follows in terms of the calculated residual strength and the prescribed minimum permissible strength P_p.

The residual strength diagram differs for different components of the structure and for different crack locations.

A critical crack a_c is one that will cause fracture in service. The value a_p is the tolerable crack size that will not allow fracture at the design load.

Crack growth curves are used to determine when a crack might reach a_p. At some crack size a_o, the crack grows in time, and using the crack growth curve allows one to predict when a_p will be reached.

Crack growth and fracture

Crack growth occurs slowly during normal service loading. Fracture is the final event and often takes place very rapidly.

Crack growth takes place by one of five mechanisms:

- Fatigue due to cyclic loading
- Stress corrosion due to sustained loading
- Creep
- Hydrogen-induced cracking
- Liquid metal-induced cracking

Even at very low loads, there is still plastic deformation at the crack tip because of the high stress concentration.

Crack growth by stress corrosion is a slow process in which the crack extends due to corrosive action (often along grain boundaries) facilitated by atomic disarray at the crack tip.

Fracture can only occur by one of two mechanisms: cleavage or rupture. Cleavage is the splitting apart of atomic planes. Each grain has a preferred plane and the resultant fracture is faceted.

Ductile rupture occurs around particles and inclusions, which are always present in a metal or alloy. First, the large particles let loose or break away from the bonding, resulting in widely spaced holes close to the crack tip.

Eventually, voids are formed at many locations, and these voids eventually join up to form a fracture. The resultant fracture surface looks dull.

Both cleavage and rupture are fast processes. Cleavage fractures can travel as fast as 1 mile/s and dimple ruptures as fast as 1500 ft/s.

Damage tolerance

Fracture mechanics methods have been developed to analyze fracture, to obtain the fracture stress (residual stress), and to analyze fatigue crack growth and stress corrosion crack growth. Creep crack growth is still in the research phase.

In stress corrosion cracking, the crack growth times are usually so short that crack growth analysis is often unimportant, and the focus is on crack growth prevention.

Failure analysis

Failure analysis is a forensic analysis of the failed parts. The objective of a failure analysis could be various, including some of the following: academic interest, to know the cause and mode of failure to develop better material, to assign the responsibility for the cause of the failure, to meet the mandatory or regulatory compliance, etc. Failures, as discussed earlier, can cause damage to life and property, and it is sometimes necessary to conduct the analysis in support of a legal necessity.

The process of failure can vary from simple to complex that may involve a coordination of experts from several disciplines, which may not be limited to various disciplines of engineers but may extend to other sciences including, for example, mathematical modeling, physics, or chemistry.

The process involves planning a failure investigation, sequencing the activities, drawing out a team, and planning and coordinating their activities and progress. To chart the progress of the investigation, the leader of the investigation is required to constantly review the progress and finding of each expert and, if necessary, correct the course of the investigation, and reroute future activities to meet the goals of the analysis.

The planning involves following activities:

1. Reviewing the objective of the failure analysis.
2. Selecting the team and assigning the role of each individual member of the team.
3. Estimating the required tools and equipment, and providing those to the members of the team.
4. Identifying the tests, examinations, and inspection requirements that would be required for the analysis to produce the results.

After the plan for the failure analysis is made, it is time to start implementing the activities. The plan may be flexible to accommodate for any new information that may emerge during the course of the investigation. The following list of activities may be followed, but it must be noted that there is no fixed route for a good failure investigation; each failure has its own personality and will require a very carefully planned activity.

1. Collect all background information and review events leading to the failure.
2. Collect all data including engineering drawings, sketches drawn, and pictures taken, and the notes made of the conversation with witnesses and field personnel involved with the failure site.
3. Determine the history of the part including the initial manufacturing process, any repair or any previous failures of the parts, or any complementing part that may have bearing on the current failure.
4. Conduct inspection of the part and the general lay out of the site and machinery involved.
5. Understand the process and environment in which the equipment is put to service.
6. Start the investigation work.
7. Review the resulting data, test reports, and compare the available information.
8. Derive conclusion.
9. Compile the report giving the background information, describing the failure with mode of failure, cause of failure.
10. Finally, recommend corrective and preventive action.

Testing of metals

Tensile test

The tensile test is used to establish operational load limits for metals and alloys. A sample of the material is prepared so a force can be applied along its axis. A central portion of the sample is reduced so that it will experience the highest stresses.

The tensile test measures the ability of a material to support a stress (force per unit area).

The response of a tensile sample to the application of an increasing stress can be described in terms of elastic and plastic behavior.

Initially, the sample undergoes elastic elongation as it is pulled. As increasing stress is applied, the sample undergoes permanent deformation, which is plastic strain.

A stress-strain curve is used to determine the point at which the reversible elastic strain is exceeded, and permanent or plastic deformation occurs.

Yield strength is the stress necessary to cause significant plastic deformation (usually defined as 0.2% strain).

Young's modulus or the modulus of elasticity states the relationship between stress and strain represented by the straight-line portion of the stress-strain curve. It reflects the tendency of a material to deflect under a given applied stress.

Once yielding has begun, there is significant motion of dislocations within the metal grains. Grain boundaries, phase boundaries, and other dislocations hinder their movement. As more obstacles are encountered, the stress necessary to cause continued dislocation movement becomes greater.

The maximum stress that the material can withstand before breaking is the ultimate tensile strength.

Reduction of area and percent elongation can be calculated from the broken sample. They are both indicators of a material's ductility.

Hardness test

Hardness is defined as the resistance to plastic deformation by indentation.

Brinell, Rockwell, and Vickers or Knoop are most common indentation hardness test methods. The depth or width of the impression left by the indentation is measured to indicate hardness.

The Brinell test presses a very hard ball into the surface under a standard load. Because a large impression is made, it is suitable only for large samples.

The Rockwell test forces a cone or sphere into the surface under a standard load. Different indenters and different scales are used for different hardness ranges.

Knoop and Vickers rests are called microhardness tests because of the very small indentation size. They are used to measure hardness on small samples and in small specific areas such as the heat-affected zone of a weld.

Rebound hardness tests measure the height to which a ball rebounds after being dropped on the surface. Equotip is a commercial rebound tester.

Impact test

An impact test measures the ability of a material to absorb energy during sudden loading to evaluate its tendency to brittle fracture. A heavy mass is positioned above the sample and allowed to strike the sample upon release. The difference between the potential energy of the mass before and after impact (i.e., the energy absorbed by the impact and fracture) is calculated and is called the impact energy, which is an indicator of materials' toughness.

Charpy and Izod samples are used. Both are notched so that breaking will occur in the controlled area.

In BCC material like steel, the impact energy is reduced as temperature is reduced. A series of tests done at progressively lower temperatures can be performed to determine the temperature at which the fracture mode changes from ductile to brittle. Such point on the chart is called transition temperature, as it relates to the change in the ductility of material.

Creep test

Creep is time-dependent plastic deformation that occurs at stresses below the yield strength of the material and in steel is normally of significance only at elevated temperatures.

A tensile specimen that is loaded in tension below its yield strength and heated will elongate with time. The creep strain (or elongation) against the time is plotted to generate a creep curve.

If time-to-failure is the parameter of interest, the test is called a stress-rupture test.

Fatigue test

Failure under repeated loads is called fatigue failure.

Typically, fatigue cracks initiate at some defect in the part and propagate through it as a result of the cyclic stress.

Iron-based alloys exhibit a fatigue or endurance limit—a stress below which the part can theoretically be cycled infinitely without failure.

Fatigue in a weld is an important part of the study in determining the performance and life of a structural member. Fatigue testing of weld is discussed in some detail in Chapter 5 of Section 2 in this book.

Heat treatment of steels

12

Heat treatment is the practical application of physical metallurgy discussed earlier in this book. The action is, in most cases, thermal with the aim of modifying the structure of the material to obtain desired properties. Other approaches could include thermochemical and thermomechanical processes, both of which strive to reach the same goal as plain controlled heating and cooling cycles, which are generally understood by the term *heat treatment*.

Heat treatment is defined as a combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desirable properties. The first step in heat treatment of steel is to heat the material to some temperature at or above the critical range to form austenite. Different heat treatments are based on the subsequent cooling and reheating of the austenitized material.

To understand heat treatment of steel, and any metal for that matter, it is important to fully grasp the phase diagram of that metal. We have discussed the subject "phase diagrams" in detail in Chapter 4 of this section. We shall take the most common and most applied phase diagram of Iron Carbon to discuss the heat treatment of steel. Where need is felt, other materials shall be included to drive home the point.

As stated before, phase diagrams are important tools to understand the heat-treatment process. Derived from that basic all-encompassing diagram, several different diagrams and charts are developed. Some of these are very specific to a specific material, temperature, and aimed properties. For example, an Isothermal (IT) diagram that describes the formation of austenite is called an ITh diagram, and the one that describes the decomposition of austenite is referred as a time temperature transformation (TTT) diagram. Continuous Cooling and Continuous Heating diagrams are commonly referenced to as CCT and CHT diagrams, which are also used to understand the effects of heating and cooling of steel during heat-treatment process.

During heat treatment, there is a possibility of both relaxation of residual stresses, e.g., Stress Reliving, discussed further in this chapter, which induces additional stress caused by thermal expansion and contraction. The developed thermal strain is directly in proportion with the cycle of heating and cooling. Such a relation, called *thermal strain* (σ_{th}), is easy to determine if we know, by correctly monitoring, the change in heat (ΔT), elastic modulus of the material (E), and thermal coefficient of expansion (α).

$$\sigma_{th} = \alpha\,\Delta TE$$

It may be noted that, if the thermal stress exceeds the flow strength of cooler or hotter material, permanent plastic deformation may occur in the material. Apart from the dimensional problems, this will result in possible phase changes that may induce fundamentally different behaviors and properties to the resulting material.

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TTT and CCT curves

Isothermal-transformation (IT) or (TTT) diagrams

As discussed before, the phase diagram is of little use for steels that have been cooled under nonequilibrium conditions. Isothermal Transformation (ITh) or Time temperature transformation (TTT) diagrams have been developed to predict nonequilibrium structures. The TTT diagram of eutectoid plain carbon steel is described later (Figure 1-12-1).

The curve is prepared by heating steel samples to the austenitizing temperature of 1550°F (845°C). These samples are then quenched to a set of temperatures below 1300°F (700°C); a molten bath is used in the laboratory for the control of temperature (Figure 1-12-2).

In the previous two TTT diagrams of steel, we can see that the A_e austenite is stable. The area to the left of the beginning of transformation consists of unstable austenite. The area to the right of the end-of-transformation line is the product to which austenite will transform at constant temperature.

The area between the beginning and end of transformation labeled A+F+C consists of three phases: austenite, ferrite, and carbide. The M_s temperature is indicated as a horizontal line, and temperatures for 50% and 90% transformation from austenite to martensite are noted.

The transformation product above the nose region is pearlite. As the transformation temperature decreases, the spacing between the carbide and ferrite layers becomes smaller and the hardness increases. Between the nose region of 510°C (950°F) and the M_s Temperature, an aggregate of ferrite and cementite appears, which is called bainite. As the transformation temperature decreases, the bainite structure becomes finer.

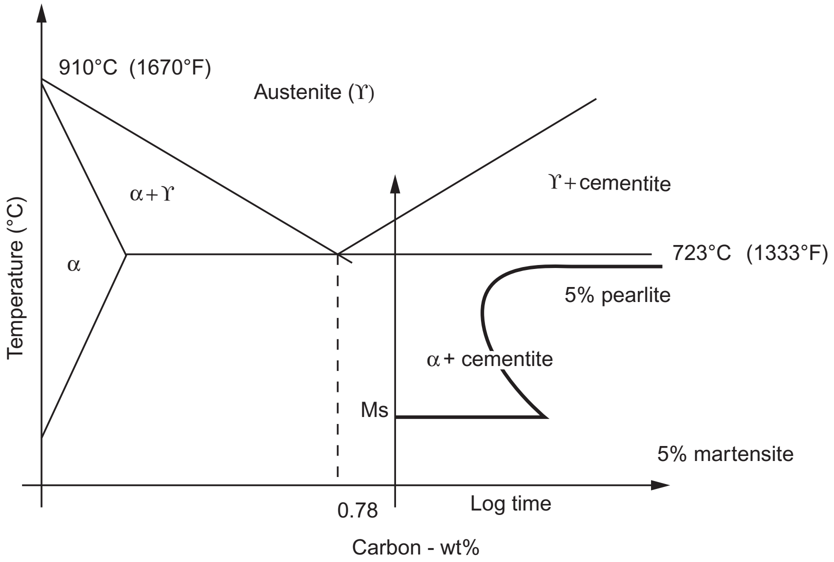

Figure 1-12-1 TTT curve of eutectoid steel superimposed on an Iron Carbon phase diagram.

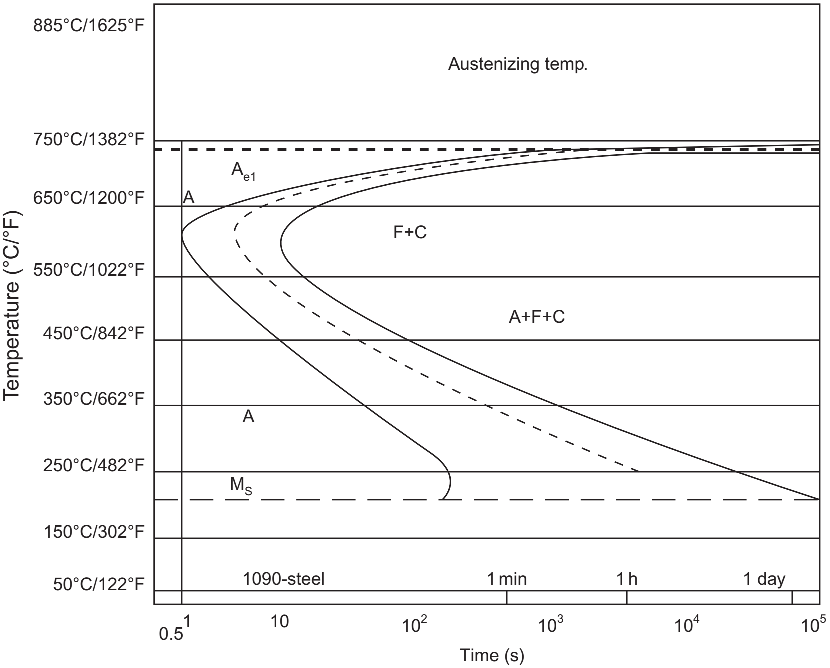

Figure 1-12-2 TTT diagram of 1090 steel.

Cooling curves

In heat treatment, the control of cooling is as important as the heating. The processes require a well-established control program to achieve the desired properties of the metal. Constant cooling rate diagrams are developed. Curves for natural cooling based on Newton's law of cooling are also developed and used. These simulate the cooling rate Jominy bar behavior.

Various cooling curves can be superimposed on the I-T diagram. In the following, a set of cooling curves are superimposed on a TTT diagram. This set is specifically developed for martempering of steel.

In the first curve (a) a very slow cooling rate typical of annealing is indicative of conventional process of tempering. The second curve (b) indicates martempering, and the third curve (c) is a curve for modified martempering.

Cooling-transformation (C-T) diagrams

The actual heat treatment of steel involves continuous cooling, thus the C-T diagram has been derived from the I-T diagram.

In general, the nose will be shifted downward and to the right as a result of faster cooling rates. Because C-T diagrams are much more difficult to derive and I-T diagrams normally err conservatively, I-T diagrams are often used to predict structures and determine critical cooling rates.

Chemical composition and austenite grain size affect the position of the I-T curve. Increasing carbon or alloying elements moves the curve to the right, transformation is retarded, and critical cooling rates are slowed down, making martensite easier to obtain.

Stress relief annealing

As the name suggests, the treatment is given to steel to relive the locked-in stresses due to manufacturing processes like forging, rolling, bending, stamping, forming, welding, etc.

The process involves heating the affected metal—either entirely or a partial section—to a temperature below the transformation range. It is usually carried out at temperatures below the lower critical line (AC_1) 723°C (1333°F) and cooling uniformly. The typical carbon steel stress relief temperature is 600–675°C (1000–1250°F) holding it for sufficient time to soak the entire thickness to a predetermined time and then cooling uniformly throughout the cross-section and surface area. As is evident, the stress relief is a time temperature phenomenon. The process may involve either microscopic or even macroscopic creep relaxation at the stress relief temperature.

Normalizing

The objective of normalizing varies. It can increase or decrease the strength and hardness of steel, homogenize and refine the grains, reduce residual stresses, etc. It is thus obvious that the process can also decrease the properties as discussed earlier. All this is dependent on the history of the material, and the heating and cooling cycle practiced. It is often seen as overlapping the function of various other types of heat treatment like annealing, hardening, and stress reliving.

The process involves austenitizing the steel, followed by controlled heating under still air. The process is both a thermal and microstructural phenomenon. Normalizing is carried out at about 55°C (100°F) above the upper-critical temperature (A_3 line), followed by cooling in still air.

Normalizing produces a harder and stronger steel, improves machinability, modifies and refines cast dendritic structures, and refines the grain size for improved response to later heat-treatment operations. As cooling is not performed under equilibrium conditions, there are deviations from the phase diagram predicted structures.

Annealing

The full annealing process consists of heating to the proper temperature and then cooling slowly through the transformation range in the furnace. The purpose of annealing is to produce a refined grain, to induce softness, improve electrical and magnetic properties, and sometimes to improve machinability. Annealing is a slow process that approaches equilibrium conditions and comes closest to following the phase diagram.

Table 1-12-1 Full annealing temperature cycle for forgings.

AISI steel	Annealing Celsius temperature	Cooling cycle from Celsius	To	Hardness range HB
1018	855–900	855	705	111–149
1020	855–900	855	700	111–149
1025	855–900	855	700	111–187
1030	845–885	845	650	126–197
1040	790–870	790	650	137–207
1050	790–870	790	650	156–217
1060	790–845	790	650	156–217
1070	790–845	790	650	167–229
1080	790–845	790	650	167–229
1090	790–830	790	650	167–229

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Annealing involves several thermal cycles, and they are classified based on the maximum level of temperature reached.

- **Subcritical Annealing:** Heating below the lower critical temperature A_1.
- **Intercritical Annealing:** Heating above A_1 but below upper critical temperature A_3 for hypoeutectoid and A_{cm} for hypereutectoid steels.
- **Full annealing:** Heating above upper critical temperature A_3.

Table 1-12-1 indicates the recommended temperatures and cooling cycle for full annealing of various carbon steel forgings.

Spheroidizing

In hypereutectoid steels, the cementite network is hard and brittle and must be broken by the cutting tool during machining. Spheroidizing annealing is performed to produce a spheroidal or globular form of carbide and improve machinability. All spheroidizing treatments involve long times at elevated temperatures to produce a structure of globular carbide in a ferritic matrix. Application of spheroidizing is discussed in the chapter about Cast Iron.

In general, spheroidizing is accomplished by following practices.

1. Heating at a temperature just below Ae_1 and holding at that temperature for a prolonged time.
2. Alternate heating and cooling between a temperature range of just above Ac_1 and just below Ar_1.
3. Heating to a temperature above Ac_1, followed by either slow cooling in the furnace or holding at a temperature just above Ar_1.
4. This method is applicable to steel that has a carbide network like hypereutectoid steels. The method involves cooling at a suitable rate from the minimum temperature at which carbide is dissolved to prevent reformation of the carbide network, followed by reheating in accordance with either method Number 1 or 2.

Tempering

Steel in the as-quenched martensitic condition is too brittle for most applications. High residual stresses are induced as a result of the martensite transformation. Therefore, tempering or drawing nearly always follows hardening.

Tempering involves heating the steel to some temperature below the lower critical temperature and thus relieving the residual stresses and improving the ductility and toughness of the steel. There is usually some sacrifice of hardness and strength.

Hardness decreases and toughness increases as the tempering temperature is increased. However, toughness drops when tempering is performed in the temperature range of 200–430°C (400–800°F). Residual stresses are largely relieved during tempering in this temperature range.

Certain alloy steels exhibit temper brittleness when tempered in the 538–675°C (1000–1250°F) range followed by slow cooling. Molybdenum has a retarding effect on temper embrittlement.

Martensite is a supersaturated solid solution of carbon trapped in a body-centered tetragonal structure and is metastable. As energy is applied during tempering, the carbon is precipitated as carbide, and the iron will become bcc. As the tempering temperature is raised, diffusion and coalescence of the carbides occur, and the final product is called tempered martensite.

Different types of tempering are known to the heat-treaters and are listed here with brief descriptions.

Austempering of steels

Carbon and low alloy steels are austempered prior to hardening. The important factors to note about the austempering process is that the rate of heating assumes secondary importance to maximum temperature attained throughout the section of the steel, holding (soaking) time at the temperature, and the cooling rate. The thermal conductivity of steel, thickness of the section, spaced or stacked furnace loading method, the nonscaling or scaling atmosphere of the furnace, and the circulation of heat in the furnace are the important variables to the success of this tempering process.

Martempering

The term *martempering* is used for a process carried out by heating the steel and castings to elevated temperature (austenitizing) and quenching in a hot fluid medium, usually kept above martensitic M_S point, of hot oil, salt baths, fluidized particle beds, etc. and stabilizing the material at that temperature by holding for sufficient time in the medium. This is followed by air-cooling at a slow rate to maintain an easy temperature gradient between outer and inner heat at the cross-section of the steel or casting. The process involves formation of martensite, hence avoidance of residual stresses is of great importance. This is followed sequentially by cooling to room temperature and subsequent conventional tempering to temper the primarily brittle martensite microstructure. Figure 1-12-3b describes the difference between conventional quenching and martempering.

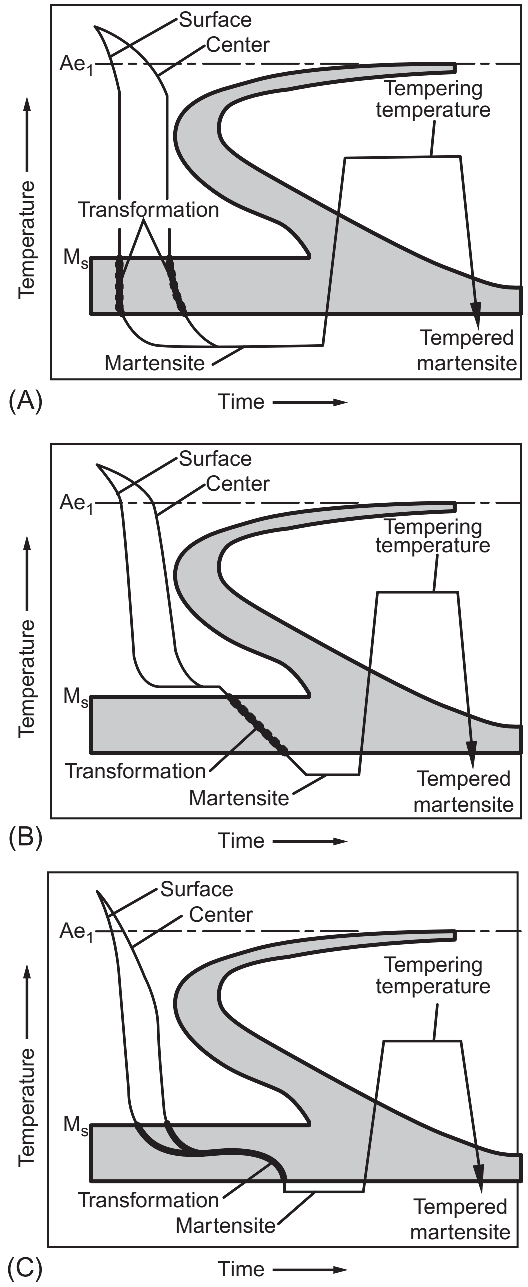

Figure 1-12-3 TTT diagram with superimposed cooling curves showing quenching and tempering. (a) Conventional process, (b) martempering, (c) modified.
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The procedure's principal aim is to reduce residual stresses, distortions, and development of cracks.

Hardening

Hardenability is related to the depth of penetration of the hardness. It is predicted by the Jominy test. The test involves uniformly heating a bar that is 4 in. long to the proper austenitizing temperature. The heated bar is then quenched by a controlled water spray.

A plot of the hardness versus distance from the quenched end is made. Because each spot on the test piece represents a certain cooling rate, and because the thermal conductivity of all steels is assumed to be the same, the hardness at various distances can be used to compare the hardenability of a range of compositions.

Hardening by martensite transformation

Under slow or moderate cooling rates, carbon atoms have time to diffuse out of the (fcc) austenite structure so that the iron atoms can rearrange themselves into the bcc lattice. This γ to α transformation takes place by nucleation and growth and is time dependent.

Faster cooling rates do not allow sufficient time for the carbon to diffuse out of solution, and the structure cannot transform to bcc with the carbon atoms trapped in solution. The resultant structure—martensite—is a supersaturated solid solution of carbon trapped in a body-centered tetragonal structure. This is a highly distorted structure that results in high hardness and strength.

Martensite atoms are less densely packed than austenite atoms, so a volumetric expansion occurs during the transformation. As a result, high-localized stresses produce distortion in the matrix. The transformation is less diffusion and small volumes of austenite suddenly change crystal structure by shearing actions. It proceeds only during cooling and stops if cooling is interrupted. The temperature at the start of the martensite transformation is known as the M_s temperature and, at the end, the M_f temperature. Martensite transformation cannot be suppressed or the M_s temperature changed by changing the cooling rate. M_s is a function of chemical composition only.

Martensite is never in a state of equilibrium although it can persist indefinitely at or near room temperature. Martensite would eventually decompose into ferrite and cementite.

Case hardening and carburizing

Another hardening method called case hardening involves carburizing, nitriding, or nitrocarburizing of the outer skin of the material to attain a hard outer surface (case) while retaining the softer and tougher inner core. The process involves availability of a carbon source; a furnace is used to attain the required temperature in a controlled environment that may be, in some cases, the carburizing gases during preparation of the components to be case hardened.

Many steel forgings are heat-treated to develop a hard wear-resistant surface while retaining the soft tough core. Such properties can be obtained in low carbon steel forgings by case-hardening using either a carburizing or nitriding process.

The process variables for carburizing include:

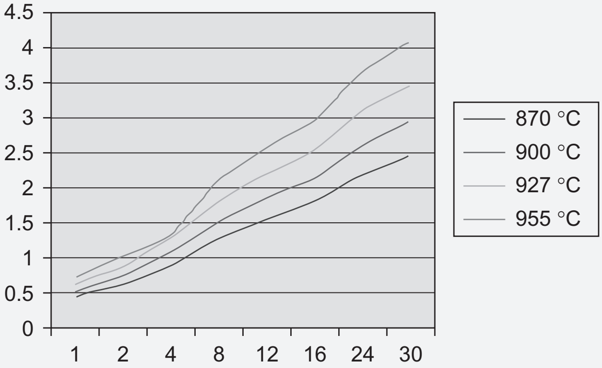
1. Temperature and its accuracy to achieve required degree of hardness, because the diffusion rate of carbon in steel increases with increasing temperature. The increase in carbon absorption from 870°C (1600°F) to 925°C (1900°F) is about 40%.
2. Time the temperature is held to austenitize the case of the steel is an important variable that would determine the depth of the hardness in the case. A longer time would austenitize deeper in the case, thus allowing more deeply hardened case. Table 1-12-2 describes the effect of time on the depth of thickness on steel case.
3. A carburizing atmosphere when the main constituents of the atmosphere are CO, N_2, H_2, CO_2, H_2O, and CH_4. Out of all these, only nitrogen (N_2) is an inert gas; the rest of the gases are present in atmosphere and are at equilibrium from the reversible reaction.

Various case hardening methods are listed here:

- Gas carburizing

Table 1-12-2 Plot of total case depth versus carburizing time.

Time (h)	870°C (mm)	900°C (mm)	927°C (mm)	955°C (mm)
1	0.46	0.53	0.64	0.74
2	0.64	0.76	0.89	1.04
4	0.89	1.07	1.27	1.3
8	1.27	1.52	1.8	2.11
12	1.55	1.85	2.21	2.59
16	1.8	2.13	2.54	2.97
24	2.18	2.62	3.1	3.66
30	2.46	2.95	3.48	4.09



This includes carbonitriding or gas nitriding processes involving the use of ammonia gas (NH_3) that produces nascent nitrogen that enters the case of the steel, increasing the hardness. The nitriding temperature ranges from 450 to 620°C (850–1150°F); the most effective results are obtained at about 510°C (950°F). The process of nitriding is suited to alloy steels compared with the carburizing process, which is most suited to low-carbon steel.

- Pack carburizing
- Liquid carburizing (cyaniding) uses a potassium cyanide (KCN) or sodium cyanide (NaCN) bath at about 845°C (1550°F). At this temperature, the steel will absorb carbon and nitrogen from the bath to a depth of about 0.125 mm (0.005 in.) within 15 min. A longer time in the bath will allow the steel to harden to the depth of about 0.25 mm (0.10 in.). To give full hardness to the case (surface) of the steel, the material is quenched in water or brine immediately after removing from the cyanide bath.
- Vacuum carburizing, which also involves the plasma (ion) process.

Liquid salt bath nitriding

Salt bath nitriding, also known as *ferritic nitrocarburizing (FNC)*, is a liquid salt bath nitriding process and is a commonly used case-hardening technique. The process provides advantages of surface hardness and corrosion resistance while also maintaining the core ductility of the steel material.

Nitriding is a thermochemical reaction; the result of the process is the formation of a thin outer layer of ϵ-iron (epsilon iron) nitride (Fe_3N). The formation of this thin layer is caused by a high concentration of nitrogen in the bath environment, which reacts with the iron surface of the steel.

Nitriding is a popular case-hardening technique renowned for the qualities it delivers at relatively low process temperatures. As stated earlier, salt bath nitriding is one of the most popular ways to achieve these results.

It is frequently used as a case-hardening method, because of the following advantages the process offers:

- Increased hardness and wear resistance at part surfaces while the cores remain softer and more ductile.
- Increased corrosion resistance.
- Significantly reduced risk of distortion due to a comparatively lower treatment temperature leading to a reduced risk of distortion during treatment.
- Salt bath nitriding is a thermochemical process in which nitrogen and carbon are diffused simultaneously into the surface of the material. The high concentration of nitrogen chemically combines with iron and other nitride-forming elements to produce an outer layer of epsilon iron nitride (Fe_3N) which is thin, hard, and ductile.

The process:

Before nitriding, the components have to be thoroughly cleaned and degreased. Any surface contamination from grinding particles, oil, metal chips, etc. are completely removed. Presence of any of these surface blemishes would result in an uneven formation of the nitrided layer. This can cause holiday (cracks) in the coating, which leads to flaking and corrosion.

After cleaning, the parts are dried and preheated, and then transferred to the actual nitriding environment, called a nitriding bath.

The various nitriding processes can be differentiated mainly by their nitrogen source and the energy supply.

Salt bath, gas, and plasma nitriding have different advantages regarding investment cost, process time, environment, safety, and quality. The properties of the resulting nitrided or nitrocarburized surface are, in many cases, independent of the production process. The required case depth is determined by the application of the nitrided component and is a function of time and temperature. This implies that, to an extent, the case depth can be controlled and regulated by variation of time and temperature.

The competitiveness of titanium alloys is due to their high strength-to-weight ratio, and heat and corrosion resistance. At the same time, the low surface hardness and wear resistance along with poor high-temperature oxidation resistance are seen as their major disadvantages. Nitriding is one of many treatments aimed at improving their tribological characteristics.

After slow cooling, precipitation in the diffusion zone is possible. The simplified morphological schematic, emphasizing the growth sequence, is shown in Figure 1-12-4.

Process of quenching

Cooling proceeds through three separate stages during a quenching operation.

Vapor-Blanket Cooling describes the first cooling stage when the quenching medium is vaporized at the metal surface, and cooling is relatively slow. Vapor-Transport Cooling starts when the metal has cooled down enough so that the vapor film is no longer stable, and wetting of the metal surface occurs. This is the fastest stage of cooling. Liquid Cooling starts when the surface temperature of the metal reaches the boiling point of the liquid so that vapor is no longer formed. This is the slowest stage of cooling.

Heat treatment of nonferrous material

Nonferrous material, especially the forgings, are heat treated to acquire additional properties or to improve existing properties.

Heat treatment of copper and copper alloys

Pure copper and some copper alloys can be work-hardened and strengthened. The original grain structure of metal completely changes at 590°C; this happens without any appreciable growth in gains. With this knowledge, we can work with copper and copper alloys and anneal them to significant ductility. They can also be annealed by heating them to about 590°C (1100°F), holding the material at this temperature long enough to let the heat fully penetrate the core of the material and allow the material to cool to room temperature without any regulation of the cooling rate.

Brass can also be annealed in a similar way by heating it to its recrystallization temperature of 590°C and cooling it to room temperature. The rate of heating or cooling has no apparent effect on the grain size of the metal.

Bronze can be similarly heat-treated to correct the hardening effect of cold-working. The metal is heated to the recrystallization temperature and cooled to room temperature.

Heating to above the recrystallization point and rapid cooling hardens aluminum bronze. This hardens and strengthens the material, and such hardened aluminum bronze is best suited for the tools used in a no-spark area, and are often specified to be used in an inflammable and explosive environment.

Heat-treating aluminum and its alloys

Cold-worked aluminum alloys get strain hardness, and this requires that the material is annealed. The recrystallization temperature of alloys may vary from 340 to 400°C (650–750°F); the temperature and the rate of heating is specific to the alloy and must be carefully applied.

Sometimes, aluminum-copper alloys are also solution heat-treated, which is dependent on the changing solubility of aluminum for the constituent of $CuAl_2$ during heating and cooling of the material in a solid state. If an alloy containing up to 4.5% copper is reheated to a temperature of about 510°C (950°F) for a considerable time extending to about 14 h, most of the $CuAl_2$ present in the annealed alloy would have dissolved. When this solid solution structure is quenched rapidly in water, most of the $CuAl_2$ will remain in solution in the metal. This treatment improves the corrosion resistance of this alloy and increases the tensile strength.

Heat-treating titanium

Parts fabricated of titanium are often used for reduction of weight, but this can compromise the strength of the structure. Like steel, titanium has allotropic structures that allows the metallurgist to alter the material's properties to some degree. Case hardening is one of those heat-treatment options that is frequently used. Case hardening improves the strength while retaining the core ductility of titanium.

In principle, all major nitriding techniques can be used to increase the properties of titanium components. However, gas nitriding has some disadvantages: it requires higher time and temperature to nitride, for example, gas nitriding requires a much higher temperature range (650–1000°C), and time can be as high as 100 h. This reduces the fatigue life of the component. For Ti-6Al-4V alloy, a typical compound layer of 2–15 μm forms with a surface hardness between 500 and 1800 HV.

By comparison, the plasma nitriding of titanium alloys is conducted at temperatures of 400–950°C and a substantially shorter time from 0.5 to 32 h, generating a compound layer with a thickness of approximately 50 μm. A reduction in fatigue strength may be eliminated by lowering the nitriding temperature.

Ion beam nitriding, using nitrogen at temperatures of 500–900°C for up to 20 h produces a 5–8-μm-thick compound layer with microhardness of 800–1200 HV on Ti-6Al-4V alloy.

Also, laser nitriding is applicable to titanium, but surface case has a tendency to crack. An attempt was made to apply the diode laser gas nitriding technique to Ti6Al4V alloy, commonly used for rotors and blades of engines in power generation. The laser surface melting of the substrate surface in a mixture of nitrogen and argon leads to an increase in surface hardness of up to 1300 HV0.2, although the outcome depends on process parameters.

The formation of the nitrided layer on titanium involves several reactions taking place at the gas/metal interface and within the metal. At the nitriding temperature below the Ti polymorphic transformation, the α-Ti phase exists. First, the nitrogen absorbed at the surface diffuses into the titanium, forming an interstitial solution of nitrogen in the hcp titanium phase α-Ti(N) and building the nitrogen concentration gradient. After exceeding the solubility limit, the Ti_2N phase is formed. During further increase in the nitrogen concentration at the gas/metal interface, TiN is formed as specified in Figure 1-12-4.

$$\alpha\text{ - Ti} \rightarrow \alpha\text{ - TiN} \rightarrow \mathrm{Ti_2N} \rightarrow \mathrm{TiN}$$

Figure 1-12-4 Schematics of the morphology development during nitriding of titanium.

Heat-treating furnaces

Various types of furnaces are used for heat-treating steel. The type of treatment required, the size and shape of the equipment or parts, the volume of the work, production output, and the economics of the work are the factors that need to be considered when determining what type of furnace to use for a specific work.

Batch type or continuous type furnaces are often the selection where the volume of production output is large. These furnaces are equipped with temperature control devices. They also control the atmosphere of the furnace chamber, which give such furnaces a distinct advantage over the quality of the work output. The handling of charge and extraction from the chamber and moving to the next stages like cooling cycle, moving to the quenching bath, etc. is often mechanized.

Furnaces may be oil-fired, gas-fired, or electrically heated. They may be further classified by the following items:

Direct-fired furnace: In this type of furnace, the steel is in direct contact with the hot gases of combustion.

Semimuffled Furnace: In this type of furnace, the gases are deflected from the parts and only the heat is allowed to circulate around the parts being heat-treated.

Muffled furnace: In this type of furnace, the heating gases are burned in a separate chamber and only the radiant heat is allowed to come in contact with parts. This furnace has an advantage over the control of the heating environment around the parts.

Electric furnaces are a muffled type in which resistors contained in a muffler do the heating. The heat is radiated to the steel in a controlled environment essential to protect the steel as well as the heating sources from oxidation damages. The temperature is controlled and monitored much more efficiently as the heating source is much stable than the gas- or oil-heating furnaces. The oxidation, scale formation, and decarburization in the furnace environment, are also controlled by creating an artificial environment by introduction of gases, which are commonly a mixture dominant with reducing gases, like carbon monoxide (CO) or hydrogen (H_2). The key advantage of an eclectic furnace is that the parts come out with clean surfaces, free from oxide scales, and also that temperature control is much better.

The mechanical attachments that improve the furnace performance are rotary hearth, rotary drum belt conveyor, and tilting hearth mechanism. Because of better control of temperature and environment, these furnaces are often used as brazing furnaces.

Liquid heating bath

In immersion heating furnaces, the liquid baths are useful in routine hardening and tempering operations. It is quick, provides uniform application of heat in all parts of the parts being heated, and can be used as a batch furnace for a number of components at a time. The other advantages are clean heating without surface oxidation and control over any possible distortion of material being heat-treated. Generally, there are three basic types of baths that are used:

Oil baths are used to heat steel for tempering treatment up to 315°C (600°F). A higher temperature is difficult to achieve due to the flammability of oils and also the fact that, at higher temperatures, the residue of the oil deposit on parts is very difficult to remove, and it works counter to the main objective of producing clean parts.

Lead baths are capable of achieving higher temperature ranging from 340 to 870°C (650–1600°F) and is suitable for tempering high-speed steels and alloy steels. The lead oxidation is one major issue with these baths, and the bath must be protected with molten salts and charcoal from oxidizing. Steel dipped in a lead bath must be protected from what is referred as “lead sticking” by application of a thin layer of salts.

Salt baths are useful for a variety of treatments to steel and other alloys. Steel can be heated in a salt bath for annealing hardening or tempering. This is possible because salt baths have greater temperature range from 150 to 1300°C (300–2400°F). Salts react dangerously in several environments, and some of the salts like cyanide salts emit dangerous fumes. This require proper health and safety precaution when working in these environments.

Because salts do not have a universal reaction with different materials, the selection of a specific salt for specific metal and alloy must be made. A salt that is neutral to the metal must be selected.

Salt baths are often used for heat treatment of aluminum and its alloys. This allows for better control and uniform heating of the parts that are heat-treated. Sodium nitrate baths are common practice for aluminum alloy heat treatment.

Section 2

Welding Metallurgy and Welding Processes

Introduction

1

There have been discussions and sometimes arguments when describing if welding is an art or a science. Mundane as it might appear, the question is pertinent. And in my experience, some well-meaning experts often miss the point as to which part about the term "welding" they are referring to support their arguments. Welding as the physical and practical part of joining two materials in most part is an art; however, the study of the heat and melt flow solidifications prediction, and prediction of a material's behavior under heating and cooling cycles associated with the term *welding* is a science. Hence it is both an art and science of joining metals by use of adhesive and cohesive forces between metals by welding, brazing, and soldering, and some of these joining processes produce metallurgical bonds.

Both process metallurgy and physical metallurgy discussed in previous sections of the book are involved in welding. Welding is a unique metallurgical activity as it involves a series of metallurgical operations similar to metal production like steelmaking and casting but in a rapid succession and on a very small scale. Generally, the thrust of the study is on the material's behavior during application of localized heat, cooling, and solidification physics.

Welding is often compared in a very rudimentary way with casting. The comparison with casting involves the fact that, in welding, a volume of molten metal is solidified (cast) within the confines of a solid base metal (mold). The base metal may have been preheated to retard the cooling rate of the weld joint, just as casting molds are preheated to slow down cooling and reduce "chilling" of the casting. Upon solidification, the weld deposit or casting can be directly put into service, as the welds are often used in as-welded condition or may be heat-treated or worked on as required. However, such comparison is not an accurate depiction of the welding process. For example, in welding, the base metal "mold" is part of the weld, unlike the mold of a casting, which is removed after solidification. So, unlike the casting process, what happens to the "mold" is of significance in welding. Unlike casting, in welding the solidification and the nucleation of weld metal takes effect on the basis of the base metal grain structure that is just adjacent to the molten metal of welding, and a unique set of metallurgy is created in the base metal that is heated to above austenitic temperature range. Tis small band of base metal is called the heat-affected zone (HAZ). We shall discuss this phenomenon in more detail in this section of the book.

Welding involves a small area relative to the full size of the structure base material. Thus, a weld is a very small mass of metal, mostly two metals that are heated very rapidly by intense heat and cooled rapidly. The dissipation of heat is via all three modes: Conduction, Radiation, and Convection. Often, the large surrounding mass of colder base metal is heated by the conduction process, which is the major source of heat transfer from a weld. The heating and, after welding, the cooling process is dynamic; equilibrium conditions are seldom seen in conventional welding operations and, in fact, welding conditions represent a great departure from equilibrium. That is

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the reason weld zones often display unusual and a verity of structures and properties, all this within the confines of a very small area affected by welding process.

It is thus important that a welding engineer have very good understanding of "HEAT" in welding. The understanding of heat generation and physics of welding are important steps in the making of a good welding engineer. In the next chapter, we start with basic understanding of physics of welding. We will review the process of heat generation, which is an essential part of the welding processes; the cooling, nucleation, and solidification physics of molten weld metal; and its effect on the parent metal. In that process, we will also review heating rate, peak temperature, HAZ, and the changes these bring in the properties of weld metal and the metal being welded.

Welding is carried out based on a well thought-out and specific plan to attain the required material properties. Many regulatory and industrial specifications have a well-developed process to activate the plan. Such plans are called *welding procedures* and *welding qualifications*. Following is a brief discussion on welding procedures and their role in a welding application.

Welding procedures

A welding procedure is a statement of execution, a specific plan prepared by the welding contractor. The procedure details a listing of various variables associated with the proposed welding process giving an assurance that the resulting weld would guarantee that the required mechanical and metallurgical properties will be met. Any format of form may be used to develop a welding procedure giving essential details. Some international specifications, especially addressing the welding requirements, have developed a format for this purpose. AWS D1.1 has E-1 form for prequalified procedures; similarly, ASME Section IX of Boiler and Pressure vessels code has a set of such forms for welding specifications, welding qualification records (PQRs), and welders' qualification records; they are numbered as QW-482, QW-483, and QW-484, respectively. Other international standards for welding are EN ISO 15609-1, EN ISO 15609-2, EN ISO 15609-3, EN ISO 15609-4, EN ISO 15609-5, and EN ISO 15614. Since the last revision, EN ISO 15614 has 12 parts dealing with specific topics on welding various materials like steel, aluminum, cast iron, titanium, copper, etc.

The plan details all essential and nonessential variables important to achieve the quality of the weld. These variables are welding process-specific. Some of these variables are discussed in this part. In ASME section IX, these variables are listed specific to the particular welding process; they are subdivided into essential, supplementary essential, and nonessential variables. However, these variables are not specific to ASME but are in general agreement with welding technology.

Essential variables are those in which a change, as described in the specific variables, is considered to affect the mechanical properties of the weldments, hence any change shall require requalification of the welding procedure. The Supplementary essential variables are required for metals for which other Sections specify notch-toughness tests and are in addition to the essential variables for each welding process.

The Nonessential variables, on the other hand, are those in which a change, as described in the specific variables, may be made in the WPS without requalification.

Some special process, like corrosion-resistant and hard-surfacing weld metal overlays, may have different additional essential variables. Only the variables specified for special processes shall apply. A change in the corrosion-resistant or hard-surfacing welding process requires requalification.

The correct electrode diameter is one of the variables, and when used with the proper amperage and travel speed, produces a weld of the required size in the least amount of time. Selection depends on the thickness of the material being welded, the position of welding in relation to the gravity of the Earth, and the type of joint to be welded. The welder's experience is also important because more skill is required to control the weld puddle in out-of-position welds, the different types of electrode coverings, and fluxes. Inexperience may lead to poor quality welds that may have defects such as inclusions and porosities in the final welds.

Welding current can be either direct or alternating, depending on the process, type of electrode, available power supply, and material being welded. DC provides a steadier arc and smoother transfer as well as good wetting action and out-of-position control. Reverse and straight current polarities are used for specific applications. Reverse polarity produces deeper penetration, and straight polarity produces higher electrode melting rates.

Physics of welding

2

The physics of welding deals with the complex phenomena typically associated with welding. The study involves knowledge of electricity, magnetism, heat, light, and sound. While studying them, it is essential that the welding engineer familiarizes and learns to use the correct terminology, as this helps to communicate effectively with fellow welding personnel. Over the years, the American Welding Society has developed a library of these terminologies, AWS A-3.0-94 "Standard Weld Terms and Definitions," and they are actively used and understood worldwide. It is recommended that these terminologies be used and referenced while conversing about welding.

For the purpose of this chapter, we shall define and explain a few important terms and their meanings as applicable to welding engineers.

Heat

Heat is the commonly used term for energy. This energy resides in the kinetic motion of atoms in any substance.

Heat flow challenges that are faced by the welding engineer are very complex, and often it is very difficult to develop a meaningful mathematical model, unless a complex laboratory environment is easily available. It is essential that the welding engineer understands the physics of heat flow and heat transfer associated with the welding process. The thermal energy can be transferred from one body to another by one of the following three methods.

1. Conduction: This transfer is via contact of two metals; a temperature gradient is necessary for the transfer of the heat by this method.
2. Radiation: Unlike conduction, no physical contact is necessary for radiation transfer of heat. The actual transfer is through photon emission and is captured by the target material.
3. Convection: This method is generally allocable to heat transfer in fluids; in this method of transfer, the fluid motion of hotter masses transfers heat to the cooler parts of the fluid in a cyclic motion until all fluid has reached an equilibrium of heat.

The heat in welding is generally an application of localized heat or, in other words, it is a concentrated heat applied at the point of the desired bond; the source of this heat could be various. The high-energy density heat source is generally applied to the prepared edges of the material to be welded. Thermit, fuel gases, furnace heat, electron beam, laser beams, electrical resistance, electric arc, and friction heat are some of the commonly used heat-producing sources for welding. The processes that use an external source of heat are usually identified by the type of heat source.

In welding, the transferred power is the rate at which energy is delivered per unit time from the heat source to the work-piece, which is expressed in watts. Thus the energy density, i.e., the transferred power per unit area of effective contact between

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the heat source and work-piece, is expressed in watts/meter^2. The heat source is often qualitatively compared in terms of temperature, which is applicable in terms of oxyfuel welding or any of the arc welding processes, but such comparison is not accurate in terms of electron-beam or laser-beam welding sources. The evolution of welding processes has been predicated, in large measure, on the development of high-energy density of the heat source. Energy density is an unambiguous measure of "hotness" that is applicable to all sources of heat generated by the welding process.

The transfer of heat energy from a welding source to the work-piece is a complex process. The energy density of a welding heat source cannot be expressed by a precise number. This is because of the unique conditions of each welding process. These unique conditions are identified in the following.

- It is difficult to define the precise area of contact between the heat source and the work-piece.
- The intensity of the heat is distributed nonuniformly over the contact area, and the concentrated intensity is typically at the center of the weld.

One way to regard the welding heat energy and its heat flow is to consider two distinct processes of heat transfer.

1. Heat is transferred from a source of heat to the work-piece by way of convection and radiation.
2. On the work-piece, the heat is transferred by conduction to the adjoining area.

The heat generated by various welding processes and the arc efficiency of some of the common arc-welding processes are discussed in this section.

Detail of the heat flow in welding

Fundamental to the study of welding is the study of heat flow. In welding, the application of heat source is called **energy input**. In the case of arc welding, it is arc energy input. Arc energy input is defined as the quantity of energy introduced per unit length of weld from a traveling heat source, as is the case with welding. The energy input (heat input) is expressed in joules per m or millimeter. This important measure is calculated as the ratio of total input power in watts to its velocity.

$$H = P/V \qquad [1]$$

where:

H = Energy input, joules per mm
P = Total power input of heat source, watts
V = Travel velocity of heat source, mm/s

If the heat source is an arc, to a first approximation:

$$H = EI/V \qquad [2]$$

where:

$E =$ Volts
$I =$ Amperes
$V =$ Travel velocity of heat source, mm/s

This relationship is adequate for general recording of the heat input in welding. However, if the objective is to make a precise determination of heat effects of arc on the material being welded, for example, a mathematical modeling, then net energy input, H_{net}, should be calculated, which is a function of heat, power input of source, and efficiency (see Table 2-3-2 for details) of the power source. If the efficiency is taken into Equations [1] and [2], the relationship can be described as:

$$H_{net} = f_1 H = f_1 P/V = f_1 EI/V \qquad [3]$$

where:

f_1 is the heat transfer efficiency; this is a ratio of the actual heat transferred and the total heat generated by heat source. With most consumable electrode arcs, the distinction between H and H_{net} is not important because the heat transfer efficiency, f_1, is generally greater than 0.8 and often reaches 1.0.

The primary function of most welding heat sources is to melt the metal to be welded. The quantity of metal to be melted is dictated by following.

- The size and configuration of the joint
- The number of passes
- The welding process

The melting efficiency is the fraction of the net energy input, H_{net}, that is used for melting the metal. The bead-on plate weld cross-section is shown schematically in Figure 2-2-1.

Note that sections A, B, and C in the figure represent:

A = Area of weld metal, also called reinforcement; this area represents the volume of filler metal added in the molten condition.

B = Area of base metal that is melted.

C = Cross-sectional area of the heat-affected zone.

The cross-section area of the weld metal, A_w, is net area of weld, computed as:

$$A_w = B + A \qquad [4]$$

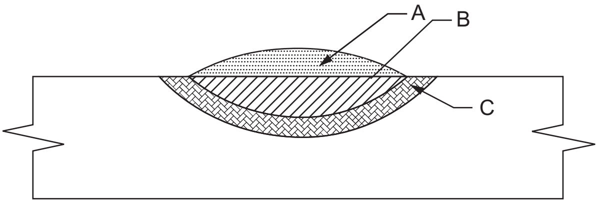


Figure 2-2-1 Dilution of material and heat in the weld nugget.

In an autogenous weld (without any addition of filler metal), the cross-sectional area of the weld, $A_{w,}$ is equal to the area of the base metal and is computed as:

$$A_w = B$$

We can see that, to melt a given area of base metal, a specified quantity of heat is required. This specific theoretical quantity of heat is Q. The amount of heat, Q, is required to melt a given volume of metal from a cold start. This quantity, Q, is a property of the metal or alloy, and is obtained by adding:

- The heat required to elevate the temperature of a solid metal to its melting point
- The heat required to convert solid to liquid at the melting point, which is the heat of fusion

A reasonable valuation of Q in J/mm^3 can be derived from following relation:

$$Q = (T_m + 273)^2/300{,}000 \qquad [5]$$

where T_m is the melting temperature of the metal or alloy in degrees centigrade (°C).

Thus, for steel, which has melting temperature of 1576°C, the quantity of heat required to melt a 1-mm^3 area is $(1576+273)^2/300{,}000 = 11.39$ J/mm^3.

Another important factor to consider is the efficiency of melting. The melting efficiency is the theoretical measure of minimum arc heat, f_2, of a weld pass that can be determined by measuring the weld metal cross-section and the net energy input. The melting efficiency, f_2, is an inverse function of minimum arc heat required to melt the metal. The value of f_2 is obtained by dividing the measure of the minimum arc heat required to melt the metal by the net energy input, and the following relationship is established:

$$\begin{aligned} f_2 &= QA_w/H_{net} \\ &= QA_wV/f_1P \qquad [6] \\ &= QA_wV/f_1EI \end{aligned}$$

The melting efficiency depends on several factors. The principal factor is identified as **the welding process**. Different welding processes have different efficiencies to produce heat, for example, varying arc-welding sources have varying arc efficiencies; thus, as a result, they have different abilities to heat. Arc efficiency of some of the common welding processes is given in Table 2-3-2.

High-energy processes are rated up to 100% efficient. Electron beam and lesser beam are examples of high-efficiency processes. In these processes, the delivered heat energy is so localized that melting takes place before any heat is conducted away. For welding, a maximum energy density of 10 kW/mm^2 or 76.5 MW/in.^{2} can be used; higher intensities would cause boiling and burning. The property of higher energy output of the electron-beam and laser-beam process is utilized for cutting and drilling of metal.

The submerged arc welding (SAW) process is a relatively very efficient process; its energy density and melting efficiency are highest among all open arc-welding processes.

Simplifying Equation [6] by substituting for H_{net} from Equation [3], a new relationship between weld metal cross-section, A_w, and the energy input is derived:

$$A_w = f_2 H_{net}/Q = f_1 f_2 H/Q \tag{7}$$

For a given welding process, there is not much variance between the heat transfer efficiency (f_1) and melting efficiency (f_2) with changes in specific welding variables like arc voltage, current, or travel speed. This highlights another constant relationship, which is the cross-section (A_w) of a single-pass weld is roughly proportional to the energy input.

With regard to **the material being welded**, the material's thermal conductivity is inversely proportional ($y = k/x$) to the melting efficiency. The effect of thermal conductivity is more pronounced with a low-energy density heat source. A good example of this is the low heat energy transfer to work-piece; only 2% of the energy is transferred when welding aluminum with an oxyfuel welding process. Thus, metals with higher conductivity are seldom successfully welded with a low-energy process.

Joint configuration and plate thickness are other factors affecting heat flow in a material by welding. These factors contribute directly to the determination of preheat temperature for welding of some materials; for this, a term relative thickness is used, indicated by the letter τ in calculations. The calculation is made using a relationship of base metal thickness, volumetric specific heat of material, the temperature differential, and net heat input.

$$\tau = \left\{ h\sqrt{P^c}\,(\mathrm{Tc} - \mathrm{To}) \right\} \Big/ H_{net}$$

where:

τ = The relative thickness of the plate
h = Thickness of the base metal in millimeters
P^c = Volumetric Specific heat (0.0044 J/mm^3 °C for steels)
Tc = The temperature at which the cooling rate is calculated. (Usually calculated at 550°C for steel; other temperature points may be used for different grades of steel.)
To = The original temperature of the material

Cooling Rate:

As we understand, the cooling rate of the weld and the adjoining material determines the end properties of the weld zone. The rate of weld cooling also allows the welding engineer to determine the heat input in welding procedures and the post-weld heat treatment to be used. Hence, it is important that this singularly important factor is in the control of the welding engineer, and control can be exercised by calculating the cooling rate in the weldment.

Using the earlier discussions of relative thickness, H_{net}, and other parameters, a welding engineer can embark on calculating the cooling rate of the weld in question.

But before embarking on such calculations, one has to determine the value of τ (relative thickness of the material at the weld). This is because the dissipation of heat is significantly altered with the geometry of the weld, in which the thickness is an important factor.

If the calculated value of τ is greater than 0.6, then the following relationship should be used to determine the rate of cooling R:

$$R = \{2\pi K\,(\mathrm{Tc} - \mathrm{To})\}/H_{net}$$

However, if the value of τ is less than 0.6, then the relationship is significantly changed, and the following should be used to determine the rate of cooling R. Note the introductions of factors like volumetric specific heat of the metal and actual thickness of the base metal at the weld.

$$R \text{ (for } \tau < 0.6) = 2\pi\ K\ P^{c}\ (h/H_{net})^{2}\ (\mathrm{Tc} - \mathrm{To})^{3}$$

In both calculations, a factor K is used. K is the thermal conductivity of the metal. For the steel, this is usually taken as 0.285 J/mm S in °C.

Heat in arc-welding processes

In the previous topic, we discussed to an extent the power and their efficiency of various welding processes. In that discussion, we took an empirical view of welding process; we now explore them in more detail, giving emphasis to the welding processes, their heat processes, and their efficiencies. A large number of welding processes use electric arc as the source of heat for fusion, because of its concentration and ease of control. An electric arc consists of relatively high current discharge sustained through a thermally ionized gaseous column called plasma.

The power of an arc may be expressed in electrical units as a product of current passing through the arc and voltage drop across the arc. Given a typical current of 250 A and 25 V as voltage, the power generated is 6250 W. That will be about 6250 J/s or 5.93 Btu/s of heat generation. Not all the generated heat is utilized in welding. There is significant loss of heat caused by spatter and heat dissipation through convection, conduction, and radiation. The effective use of the generated heat is called efficiency of the process. The efficiency is expressed as a percentage of the generated heat against the actually utilized. This can range from 20% to 85% in various arc-welding processes.

Welding processes like gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), and SAW are listed in ascending order of efficiency. In other words, GTAW at 40% is the least efficient process, and SAW is the most efficient process utilizing up to 95% of the generated heat. Refer to Table 2-3-2 for more information on arc efficiency of other welding processes.

Arc efficiency is an important factor in the study of weldability, especially when slower travel speed processes are the subjects of the study. However, as the travel speed increases, the following important changes occur.

- The efficiency of heat transfer in the fusion zone also increases.
- For the constant arc energy input system, the volume of the fused metal also increases.

As a consequence of these changes in the automatic welding processes associated with process characteristics of higher speed and higher current, the arc energy input is no longer an adequate parameter to use as a factor for weldability study.

Heat in plasma arc cutting and welding

In the plasma arc heating source is the arc that is forced through a nozzle to constrict its diameter. To accomplish this extra force, higher voltage is used. When the forced arc passes through the constricted passage of the nozzle, a smaller diameter of the arc column is created. This results in following.

1. Higher density (intensity) of the arc is created.
2. The temperature of the arc is increased.

The 86 kW of power passing through a 3.2-mm nozzle with gas flow of 70 L/min would produce a power density (PD) of approximately 8.5 kW/mm^2, and the average gas temperature will be between 9700°C and 14,700°C (16,232°F and 26,492°F). At these temperatures, the resulting gas velocity would reach sonic velocity. These properties are good for plasma arc cutting. However, for a plasma arc welding (PAW) process, control of the molten pool is important thus lower gas velocities are used. More detail of the process is discussed in later parts of this book when discussing welding processes.

Heat in resistance welding

The resistance welding process uses a combination of mechanical force and heat to accomplish welding. Electrical resistance between the two work-pieces generates the heat. The heat is also generated as electrical energy of the welding current flowing through the work-pieces. The work-pieces are generally connected to the secondary circuit of a transformer that converts high voltage and low current of commercial power into high current and low voltage for suitable welding power.

The heat generated by current flow may be expressed by:

$$H = I^2Rt \qquad [8]$$

where:

H = Heat generated, joules
I = Current, amperes
R = Resistance, ohms
t = Time of current flow in seconds

The resistances that are important in these welding processes are composed of several parts:

- Contact resistance between the electrodes and the work
- Contact resistance between the work-pieces

- Body resistance of the work-pieces
- Resistance of the electrodes

The heat requirement is calculated as:

$$H \text{ in joules} = (\text{current in Amperes})^2 \times (\text{material thickness in meters}) \\ \times (\text{Time in secondsduration of current applied})$$

Approximately 1381 J (about 600 Btu/lb) are required to heat and melt 1 g of steel.

Let us consider another example wherein we use a welding machine that has a heat output of 1000 J. Assuming that the fusion zone of a weld is a cylinder of 5 mm diameter and 1.5 mm high, the fused metal would have a volume of approximately 31 mm^3 and a mass of 0.25 g. The heat required to melt this mass is 345.45 J, and the remaining heat (1000 J − 345.45 J = 645.55 J) will be absorbed by the surrounding metal.

However if a capacitor-discharge power supply unit is used to make a projection weld between two steel sheets that are each 1-mm thick, the current pulse used is 30,000 A, and weld time is 0.005 s. In this case, the calculation for the required heat (H) will be as follows:

$$H = (30{,}000)^2\,(0.0001)\,(0.005) = 450\,\text{J}$$

The lesser heat required in this case is due to the lower heat loss and localized heat application especially due to localized weld interface.

Heat in electroslag welding (ESW)

In the electroslag welding process (ESW), an electrode is fed through an electrically charged bath of molten slag. The resistance of the slag bath to the flow of current produces the heat. A majority of that heat is concentrated in the slag, which immediately surrounds the electrode tip. The quantity of heat, H, produced in the slag pool can be expressed as:

$$H = Eit \qquad [9]$$

where:

E = The voltage, volts
i = Current, amperes
t = Time, in seconds

The manner in which the heat is transferred in this process is complex; however, it is an essential tool to control the quality of the weld. The weld pool shape is determined by following variables:

- The depth and width of the slag
- Electrical variables

- Geometry of the weldments
- The dimensions of the electrode and base metal

In this process where the slag bath has a very important role in the welding current flow, the properties of the slag are important variables for good weld heat. The slag should be:

1. Stable for conduction of heat and range of current
2. Stable at operating temperature ranges
3. Low volatility at operating temperatures
4. Suitable chemical reactivity
5. Slag should be suitably viscous, for stability

The ESW can be stabilized over constant slag temperatures by maintaining a balance over the heat generated and heat lost. The geometry of the cross-section of the weld pool should be shallow with large radius of curvature. The shallow pool promotes vertical freezing that allows development of an acute angle between weld metal grains. High current and low voltage promotes shallow pools. Conversely, deep pools are produced by high voltage, high wire feed, and low currents. The slag bath should also be shallow to avoid incomplete fusion in the weld.

Both AC and DC currents are used for an ESW process. The choice significantly depends on the slag-to-metal reaction as contrasted with operating characteristics associated with other welding processes.

When direct current electrode positive (DCEP) is used, constant potential power source and wire feed technique are used.

Alternative current (AC) for similar weld quality will require higher voltage, which will result in higher welding heat as calculated using the $H=Eit$, relation discussed earlier.

Heat in welding process using chemical sources

Chemical energy stored in a variety of forms can be used for welding by converting chemical energy into heat energy. In general, these can be classified as oxyfuel welding and thermit welding (TW) processes.

Oxyfuel welding requires two fuel characteristics:

1. High flame temperature capable of melting and controlling the molten weld metal
2. A neutral or reducing atmosphere surrounding the molten pool to prevent contamination of weld metal before solidification

Most commonly used fuel gases when mixed with oxygen achieve temperatures up to 2760°C (5000°F). At maximum temperature, the flame is oxidizing hence it is not suitable for welding, as it will promote oxides and contaminate the molten weld metal.

Table 2-2-1 lists various oxyfuel gases and maximum temperature they produce in reaction with oxygen.

From the table, we note that only an oxy-acetylene (HC_2H) welding (OAW) flame is capable of developing enough heat to melt steel. Methylacetylene-propadiene propane (MAPP) can also be used for welding with some additional precautions.

Table 2-2-1 Welding gas flame temperatures.

Flame types	Maximum temperature (°C)	Neutral flame temperature (°C)
Stabilized methylactylene-propadiene burning with oxygen gas	2900	2600
Oxygen with propylene flame	2860	2500
Oxygen and propane flame	2780	2450
Natural gas burning with oxygen	2740	2350
Oxy-acetylene flame	3100	3100

Table courtesy of IAF Basic Engineering Training Manual, 1969.

Acetylene combustion in oxygen is in two phases. In the first phase, carbon is burned producing carbon monoxide, the remaining hydrogen is unconsumed. The burning takes place in the small bluish-white cone of the flame where the gases mix, and this reaction provides a heat that is most effective for welding. In the second phase, the conversion of carbon monoxide to carbon dioxide and hydrogen to water vapor takes place in the large blue flame surrounding the welding operation, and the heat of this region contributes to the preheat of the surrounding metal. The chemical reaction of the two phases of the flame is as follows:

$$C_2H_2 + O_2 \rightarrow 2CO + H_2 \tag{10}$$

$$2CO + H_2 + 1.5O_2 \rightarrow 2CO_2 + H_2O\,(g) \tag{11}$$

In the first reaction, heat is generated by breaking up of acetylene and formation of carbon monoxide. This dissociation of acetylene liberates 227 kJ/mol at 15°C (59° F), and the combustion of carbon forms carbon monoxide, which liberates another 221 kJ/mol. The total heat supplied by the first reaction is therefore 448 kJ/mol (about 500 Btu/ft^3) of acetylene.

The second reaction liberates water vapor by burning hydrogen and produces 242 kJ/mol of heat. The combustion of carbon monoxide provides 285 kJ/mol or an additional 570 kJ/mol for the reaction. The total heat supplied by the second reaction is thus 812 kJ/mol, which is a sum of 242 kJ/mol and 570 kJ/mol. This will be equivalent to about 907 Btu/ft^3 of heat.

The total heat supplied by the two phases is 1260 kJ/mol (1407 Btu/ft^3) of acetylene. The first reaction produces about 35.6% of the all heat in a very concentrated form. Remaining heat is developed by the outer feather-like part of the flame acting like a preheat temperature and thus reducing the steep thermal gradient caused by welding.

Thermit welding

TW is a process that uses heat from exothermic reaction to produce coalescence between metals. The name is derived from “thermite,” which is the generic name given to a reaction between metal oxides and reducing agents. The thermite mixture consists of metal oxides with low heats of formation and metallic-reducing agents that, when oxidized, have high heats of formation. The excess heats of formation of the reaction products provide the energy source to form the weld.

Let us consider an example; if fine aluminum particles and metal oxides are blended and ignited by an external heat source, the aluminothermic reaction will precede according to the following equation:

$$\text{Metal Oxide} + \text{aluminum} \rightarrow \text{aluminum oxide} + \text{metal} + \text{heat}$$

The most common thermit welds reactions are listed in the following table:

$$\tfrac{3}{4}\,Fe_3O_4 + 2Al \rightarrow 9/4\,Fe + Al_2O_3 \quad (\Delta H = 838\,kJ) \tag{12}$$

$$3FeO + 2Al \rightarrow 3Fe + Al_2O_3 \quad (\Delta H = 880\,kJ) \tag{13}$$

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 \quad (\Delta H = 860\,kJ) \tag{14}$$

$$3CuO + 2Al \rightarrow 3Cu + Al_2O_3 \quad (\Delta H = 1210\,kJ) \tag{15}$$

$$3Cu_2O + 2Al \rightarrow 6Cu + Al_2O_3 \quad (\Delta H = 1060\,kJ) \tag{16}$$

The theoretical estimated maximum temperature from the reactions listed earlier is 3200°C (5800°F). In practice, however, the heat ranges between 2200°C (4000°F) and 2400°C (4350°F). The ignition temperature of the thermit granules used for welding is about 1200°C (2200°F); therefore, it is safe from fire hazards if stored away from open heat sources.

Heat generated by mechanical processes

The welding processes where the required heat is generated by a mechanical process are a unique group. This group is comprised of the following known processes:

1. Friction Welding
2. Ultrasonic Welding
3. Explosion Welding

We will discuss briefly all three welding processes.

Friction Welding

Friction welding (FRW) is a process that bonds a stationary member to a rotating member by developing frictional heat between the two members. The frictional heat is generated by application of forces on the faying surfaces. As far as possible, the rotating member is maintained at a symmetrical axis, while the nonrotating member has no restriction on its geometry.

The weld is done by heat generation through the rotational speed and simultaneous application of normal force. Time is a factor in the development of heat, and application of force is required to produce a bond. The heat is a function of both these variables. It is significant to note that the radial temperature distribution is nonuniform. The highest heat is on the outer surface where the speed is highest.

In this process, the average interface temperature is below the melting temperature of either members being joined. The bond is metallurgical and is achieved by diffusion rather than by fusion. This allows joining of dissimilar metals, especially those metals that, if melted as in conventional welding, would form undesirable phases reducing weldability or making them practically "unweldable." The width of diffusion can vary significantly; in some cases, the diffusion line is difficult to define, yet in other cases it is easily detected by low power magnification.

In practice, this process utilizes one of the following methods to generate heat:

1. Relatively slow rotation and high normal force
2. High speed and relatively low normal force
3. Using an inertia process in which a rotating flywheel is disengaged from a rotating drive before the start of welding

The Welding Institute in Cambridge, United Kingdom (www.twi.co.uk), has carried out some pioneering research and development in this field.

Ultrasonic Welding

Ultrasonic welding (USW) uses high frequency vibratory energy into the weld zone to affect the weld. The use of this process is often limited to spot, straight, or circular welds on members of which at least one is of foil thickness.

The process produces a metallurgical bond in which the vibratory energy is transmitted through one or both sonotrode tips that oscillate in a plane essentially parallel to the weld interface on the secured members. The oscillating shear stress results in elastic hysteresis, localized slip, and plastic deformation at the contact surfaces, which disrupt the surface films and allow metal-to-metal contact. The produced metallurgical bond can join both similar and dissimilar metals without melting. The temperature can reach up to 35%–50% of the absolute melting point of metals being joined.

The process involves 60 Hz of electrical power that is transformed into high-frequency power through a frequency converter. The output ranges between 15,000 and 75,000 Hz, but frequencies outside this range can also be used for welding by this process. Transducers, while maintaining the frequency, achieve the acoustical conversion of high-frequency electrical power. Suitable acoustical couplers are required to transmit the energy to the sonotrode tip and into the metals being welded.

The amount of acoustical energy required for welding a given material increases with material hardness and thickness. The relationship for USW can be expressed as an approximation that can be later fine-tuned and adjusted to meet the final requirements. The empirical equation used for most common metals such as aluminum, steel, nickel, and copper in thickness up to 0.8 mm is:

$$E_a = K_1 \, (Ht)^{3/2} \qquad [17]$$

where:

E_a = Acoustical energy, J
H = Vickers micro indentation hardness number
t = Thickness of the material adjacent to the ultrasonically active tip, in millimeters or inches
K_1 = Constant, 8000 for "t" in millimeters and 63 for thickness "t" in inches

The process requires experimentations and trials to establish the precise machine settings to produce satisfactory welds in a given material and thicknesses.

Explosion Welding

Explosion welding (EXW) uses detonation of an explosive to accelerate a component, called a flyer, to high velocity as it collides with the other component being welded. At the moment of impact, the kinetic energy of the flyer plate is released as a compressive stress wave on the surfaces of the two components, forming a metallurgical bond. In this process, the collision progresses across the surface of the plates being welded forming an angle between the two colliding components. The surface films are liquefied, scarfed off the colliding surfaces, and jetted out of the interface leaving perfectly clean, oxide-free surfaces. Under these conditions, the interaction within the molecules and atoms and the resultant forces create cohesion; the resultant weld is without any heat-affected zone (HAZ).

As described earlier, the explosion provides the energy for the weld, and the detonation velocity should be within limits to produce the required impact velocity and angle between the two components. The sonic velocity within the material being welded limits the explosion velocity. This is a very important variable because, if the detonation velocity exceeds the metal sonic velocity, shockwaves will be formed. Because they are sonic velocities, they travel faster than the detonation velocity, causing spalling along the edges and fissuring at the weld interface. Controlling the amount of charge per unit area can alter the flyer plate velocity. When high-velocity explosives are used, the process will demand thick buffers between the explosive and the cladding plate.

The effect of high-velocity explosives can be surmised as:

1. Larger waves are produced with the same angle of incidence.
2. The range of angles within which waves are produced is also increased.
3. The angle of incidence at which weld waviness begins increases.
4. There is increased tendency for the formation of intermetallic compounds in the weld interface area.

The correct amount of explosive should be used. Less explosive will not be able to develop a velocity capable of welding.

The explosives used are varied such as plastic flexible sheet, cord, pressed, cast, granulated, and liquid. Standard commercial blasting caps achieve the detonation.

The detonation velocity tends to be constant throughout the explosion. The energy released by explosives is dependent on the thickness of the explosive spread and degree of confinement. These factors, along with the ingredients in the explosive used, become the variables of the detonation velocity.

Heat by focused sources

Two welding process that use focused energy are laser-beam (LBW) and electron-beam welding (EBW) processes. The beams are focused to produce heat, and they operate according to the laws of optics.

Laser-beam welding (LBW)

Laser beams are focused by the arrangement of various lenses. Electrostatic and electromagnetic lenses focus the electron beam. This results in high power densities of heat.

In LBW, a high degree of spectral purity and low divergence of laser radiation permits focusing a laser beam on an extremely precise area, resulting in power densities greater than 10 kW/mm^2 (6.45 MW/in.^{2}). The unfocused beam exiting from a laser source may be typically 1–10 mm in diameter and must remain focused to be useful for (LBW application. The focused spot size, *d*, of a laser beam is:

$$d = f\theta \qquad [18]$$

where:

f is the focal length of the lens
θ is the full angle beam divergence

The PD at the focal plane of the lens is obtained by:

$$\mathrm{PD} = 4P_1/\pi d^2 = 4P_1/\pi\,(f\theta)^2 \qquad [19]$$

where:

P_1 is the input power
d is the focused spot size of laser beam

Therefore, PD is determined by the laser power, P, and beam divergence, θ. For a laser beam operating in a fundamental mode where the energy distribution across the beam is Gaussian, the beam divergence θ is about equal to:

$$\lambda/\alpha \qquad [20]$$

where Greek letter alpha (α) is a characteristic dimension of laser, and Greek letter lambda (λ) is the wavelength of laser radiation. By combining Equations [19] and [20], we find that the PD (PD) is inversely proportional to the square of the wavelength of the laser radiation.

$$\mathrm{PD} = 4P_1\,\alpha^2/f^2\,\lambda^2 \qquad [21]$$

For a welding process, solid-state lasers and gas laser beams are used. Solid-state lasers are single crystals or glass doped with small concentrations of transition elements such as chromium in ruby or rare earths such as neodymium (Nd) in yttrium-aluminum-garnet (YAG) or glass. The industrial gas lasers are carbon dioxide lasers. Ruby and Nd-glass lasers are capable of high-energy pulses but are limited in maximum pulse rate. Nd-YAG and CO_2 lasers can be operated continuously or pulsed at very high rates.

Most metallic surfaces reflect significant degree of incidental laser radiation; in practice, sufficient energy is absorbed to initiate and sustain a continuous molten puddle. Because ruby and Nd-glass lasers have high energy output per pulse, ruby and Nd-glass lasers can overcome most metal welding reflectivity problems. However, they suffer from low pulse rates, which typically range between 1 and 50 pulses per second, which results in slow welding speed in thin-gauge material. The Nd-YAG and CO_2 lasers are capable of high-speed continuous welding, because Nd-YAG and CO_2 produces continuous high wave output, and they can also be pulsed at the rate of several pulses per second.

Electron-beam welding (EBW)

Another focused beam-welding process is called electron-beam welding. The process develops energy by bombarding the work-piece with a focused beam of high-velocity electrons. PD defines the process's ability to develop enough heat for welding. The PD in watts per unit area is obtained by the following equation.

$$\mathrm{PD} = neE/A = EI/A \tag{22}$$

where:

n = Total number of electrons per second in the beam
e = The charge on an individual electron (1.6×10^{-19} coulombs)
E = The accelerating voltage on the electrons, in volts
I = The beam current, in amperes
A = The area of the focused beam at the work-piece surface

The beam current, accelerating voltage, and welding speed are the factors that determine the depth of penetration of a focused beam.

The power concentration of 1–100 kW/mm^2 is routinely achieved, and up to 10 MW/mm^2 can be obtained for most welding. The concentration of energy is dependent on accelerating voltage. EBW is generally performed at voltages between 20 and 150 kV; higher voltage corresponds to higher PD.

EBW process has several advantages due to its focused heat source for welding; the advantages of EBW process are:

1. Welds with higher depth-to-width ratio can be successfully achieved
2. High strength of weld can be achieved
3. Ability to weld thick sections in a single pass
4. The relative low heat input results in low distortions in the base metal
5. Very narrow HAZ

The welding process involves the application of high PD, which instantly volatizes the metal; this creates a needle-like vapor-filled cavity or keyhole in the work-piece, allowing the beam to penetrate through the section of the metal to be welded. The cavity is kept open by the pressure of the vapor for the welding to proceed. The flow of the molten metal is from the front to rear of the keyhole as the weld solidifies.

Three commercial variants of the EBW process are given in Table 2-2-2.

Table 2-2-2 EBW variants.

	EBW variant description		Operating pressure
1	High Vacuum EBW	A pioneer process	13 MPa (10^{-4} Torr) or lower
2	Medium Vacuum EBW	Soft vacuum process	At 13 MPa (10^{-4} Torr)
3	Nonvacuum EBW		At 100 kPa (1 atm)

Other sources of heat in welding

The energy required for diffusion welding (DFW) is unlike arc, resistance, oxyfuel, or TW processes, although the heat is supplied by furnace. These furnaces may be electric, gas, or chemical.

The diffusion phenomenon is of prime importance in metallurgy because several phase changes occur in metal alloys that involve redistribution of the atoms. These changes occur at rates that are dependent on the speed of the migrating atoms.

DFW is a solid-state welding process that produces coalescence at the faying surfaces by the application of pressure at elevated temperatures. This process is also called by some nonstandard terms like pressure bonding, diffusion bonding, self-welding, and cold-welding.

Usually the diffusion in metal systems occurs in three different processes. These are dependent on the mode of the diffusing element.

1. The volume diffusion
2. Grain boundary diffusion
3. Surface diffusion

Each of these diffusion process modes have different diffusivity constants. The specific rates for grain boundary and surface diffusion are higher than the rates of volume diffusion.

Adolf Fick derived his first law of diffusion in 1855. It describes diffusion and is used to solve for the diffusion coefficient (D).

Fick's first law describes the diffusive flux to the concentration field; it assumes that the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient. In one (spatial) dimension, this is:

$$J = -D\,(\partial\theta/\partial x)$$

where:

- J is the diffusion flux in dimensions of [(amount of substance) $\text{length}^{-2}\text{time}^{-1}$], for example, ($\text{mol/m}^2$ s). J measures the amount of substance that will flow through a small area during a small time interval.
- D is the diffusion coefficient in dimensions of [$\text{length}^2\text{time}^{-1}$], for example, ($\text{m}^2$/s).
- ϕ (for ideal mixtures) is the concentration in dimensions of [(amount of substance) length^{-3}], for example, (mol/m^3).

- $\mathcal{X}$ is the position [length], for example, *m* (meters).

D is proportional to the squared velocity of the diffusing particles, which depend on various factors like temperature, viscosity of the fluid, and the size of the particles.

In two or more dimensions, we must use ∇, the del, or gradient operator, which generalizes the first derivative, by obtaining the value of *J* from the following equation:

$$J = -DJ = -D\nabla\theta$$

The driving force for the one-dimensional diffusion is the quantity derived from the following relationship:

$$-(\partial\phi/\partial x)$$

The driving force derived from this equation is the concentration gradient for an ideal mixture. However, for chemical systems that are not ideal solutions or mixtures, the driving force for diffusion of each species is the gradient of chemical potential for this species. Then Fick's first law (one-dimensional case) can be written as:

$$J_i = -Dc_i\,\partial\mu_i/RT\,\partial x$$

where:

The index, *i*, denotes the ith species, *c* is the concentration (mol/m^3), *R* is the universal gas constant in J/(K mol), *T* is the absolute temperature (K), and μ is the chemical potential (J/mol).

Using Fick's first law to the diffusion, for metals we derive the following basic equation for diffusion:

$$1/A\,dm/dt = -D\cdot\partial c/\partial x \qquad [23]$$

where:

dm/dt = Rate of flow (g/s) of metal across a plane perpendicular to the direction of diffusion
D = Diffusion coefficient whose values depend on the metallic system being considered (mm^2/s); minus sign expresses a negative concentration gradient
A = The area (mm^2) of the plane across which diffusion occurs
$\partial c/\partial x$ = The concentration gradient that exists at the plane in question (*c* is expressed in g/mm^3)
x = Distance, mm

The diffusion coefficient (*D*) is usually not constant. It is a function of such dynamics as temperature, concentration, and crystal structure.

The essential ingredients of the process are time, temperature, and pressure. Atomic vibration and mobility increases with increasing temperature. As the faying surfaces are brought into contact by application of pressure, diffusion across the faying surfaces is increased in both directions resulting in the coalescence required for welding.

Because it is an atomic process, the welding time is longer. The key advantages of the process are low residual stresses, which makes it possible to fabricate assemblies that require very close tolerance.

Thermal properties of some of common weldable materials are found in the following table:

	Thermal diffusivity	**Volume thermal capacity**	**Thermal conductivity**	**Melting point**		
Material	α **(m^2/s)**	Pc **(J/m^3 K)**	k **(J/m s K)**	**K**	**°C**	**°F**
Aluminum	8.5×10^{-5}	2.7×10^{6}	229.0	933	660	1220
Carbon Steel	9.1×10^{-6}	4.5×10^{6}	41.00	1800	1527	2780
9% Ni Steel	1.1×10^{5}	3.2×10^{6}	35.2	1673	1400	2552
Austenitic Stainless Steel	5.3×10^{-6}	4.7×10^{6}	24.9	1773	1500	2732
Titanium Alloy	9.0×10^{-6}	3.0×10^{6}	27.0	1923	1650	3002
Monel 400	8.0×10^{-6}	4.4×10^{6}	35.2	1573	1300	2372
Inco 600	4.7×10^{-6}	3.9×10^{6}	18.3	1673	1400	2552
Copper	9.6×10^{-5}	4.0×10^{6}	384.0	1336	1063	1945

Application of the principles of welding physics

The following section discusses the application of the principles discussed earlier in terms of preheat, postheat, rate of heating, and rate of cooling, and their effect on weldments.

Preheating

Preheating involves welding material that has been heated to a material-specific temperature aimed at reducing the cooling rate by lowering the temperature gradient. In multiple bead welds, the succeeding beads may be deposited on metal that has been preheated by the preceding beads.

The stresses caused in material by welding can cause serious limits on its application depending on factors like the material's own strength, hardness, and structural rigidity. Various stresses that affect weldments are discussed in detail in later chapters of this book. Some of the corrective measures include control of heat during welding. This is achieved by raising the material temperature to a level below its **lower transition** temperature, mostly below 450°C. This level of heating prior to welding is commonly referred to as preheating; for standard carbon steel, this temperature would be in the range of 75–150°C. Preheat is applied with the objective of reducing the cooling rate of the weld and HAZ of the parent metal. For most carbon steel, a suitably controlled welding process in combination with preheat maintenance is sufficient to control distortions, and postweld cracking is associated with increased hardness, hydrogen diffusion, and cooling stress.

Determining the need for preheat and the temperature

Preheating as discussed before is a method to establish controlled cooling; metallurgically, it's a method of controlling the formations of harmful martensite in the HAZ of steel welds. The formation of martensite especially in the presence of hydrogen in the material can be catastrophic. When welding steels that can be hardened, it is important to establish the cooling rate. With the exception of low carbon steel and austenitic steels, most of the steels in construction are hardenable. The temperature at which the cooling rate (Tc below) is calculated is often the temperature at which pearlite is formed; this is usually at the nose of the temperature curve of the material's continuous cooling transformation (CCT) diagram.

For any calculation of cooling rate or temperature, it is essential to establish if the heat dissipation is three-dimensional or two-dimensional. This is also termed as relative thickness of the weld, which is dependent on the weld geometry. There are three general characteristics for the heat flow: (1) two-dimensional, (2) three-dimensional, and (3) intermediary condition. Based on this, the metal may be termed as relative low thickness, relative high thickness, or in an intermediary thickness condition. The relative thickness is described by letter τ, and we can use the equations given in the section where we discussed heat flow to determine the relative thickness τ of a given weld material:

$$\tau = \left\{ h\sqrt{P^{c}}\,(\mathrm{Tc} - \mathrm{To}) \right\} \Big/ H_{net}$$

If we collect the welding data and use the welding current, voltage, and travel speed, we can determine the need for and calculate the preheat temperature to keep a cooling rate that would reduce the possibility of martensite formation.

For example, if we have following welding data:

Voltage (E): 23 V
Current (I): 320 A
Plate thickness: 10 mm
Welding process efficiency (f_1): 0.85
To: 25°C (77°F)
Tc: 525°C (977°F)
Travel speed (v): 9 mm/s (20 in./min)

We can calculate the energy input, H_{net}:

$$H_{net} = f_1\,EI/v = 695.11\,\mathrm{J/mm}$$

We calculate the relative thickness τ using the given equation:

$$\tau = \left\{ h\sqrt{P^{c}}\,(\mathrm{Tc} - \mathrm{To}) \right\} \Big/ H_{net} = 0.48$$

This is ≤0.6, which is indicative of two-directional heat flow, hence a thin wall condition exists. The following equation can be used to determine the cooling rate.

$$R = 2\,\pi\, k\, p\mathrm{C}\,(h/H_{net})^{2}(\mathrm{Tc} - \mathrm{To})^{3}$$

If the value of τ is somewhere between 0.6 and 0.9, then it may be necessary to calculate both thin- and thick-wall equations and establish correct values for desired cooling rate and required preheat temperature. It may be noted that the lowest calculated preheat value that gives the desired cooling rate must be used.

A case study is included in which a lifting lug weld cracked after welding.

Weld toe crack: Case Study 1

Introduction to the case:

Four can sections of an offshore platform leg subassembly were each welded with a lifting lug, also called pad-eye. On cooling, three of the four welds developed cracks at the toe of the weld.

On an 8 + 8 jacket with base bottom of about 60 m × 30 m, a can section was fabricated in the yard. The subassembly of four cans each 16 m high were fitted with lifting lugs. These lugs were cut from a 30-mm-thick ASTM A-36 plate. The cans were 1067-mm-diameter pipe that had wall thickness of 55 mm; the material conformed to API 5L 2H Grade 50, and the nominal composition is given in the following table:

	C	Mn	P	S	Si	Cb	Ti	Al	N	V
Heat	0.18-	1.15–1.60	0.030	0.010	0.05–0.4	0.01–0.04	0.020	0.02–0.06	0.012	Not intentionally added
Product	0.22			0.015	0.05–0.45					

Carbon Equivalent maximums

The carbon equivalent of the material was 0.44 calculated using:

$$\mathrm{CE} = \mathrm{C} + \mathrm{Mn}/6 + (\mathrm{Cr} + \mathrm{Mo} + \mathrm{V})/5 + (\mathrm{Ni} + \mathrm{Cu})/15$$

Mechanical Properties (transverse tests)

Yield strength, ksi (MPa)	Tensile strength min., ksi (MPa)	% elongation in 2 in. (50 mm)	% elongation in 8 in. (200 mm)
51 (352)	90 (620)	26	21

Charpy Impact Properties

The as-rolled slab Charpy V-notch tests, consisting of three transverse specimens, reported values given in the following table.

Due to the low carbon and sulfur contents, the energy of the full-size specimens will often exceed the limits of ASTM E23; therefore, subsized specimens were used.

Specimen size mm	Min. avg. energy ft-lbs (J)	Min. single value ft-lbs (J)	Test temp. F (°C)
10 × 10	30 (41)	25 (34)	−40 (−40)
7.5 × 10	30 (41)	25 (34)	−40 (−40)
7.5 × 10	23 (31)	19 (26)	−50 (−46)
5.0 × 10	15 (20)	13 (18)	−80 (−62)

Plates were additionally tested to supplementary requirements of S1, S2, S3, and S4 requirements.

All four pad-eyes were cut from same ASTM A-36 plate that was lamination checked. After cutting and fabrication and prior to attaching to the can sections, an ultrasonic testing (UT) scan was carried out to ensure there was no new opened lamination.

The abutting sides of the lifting lugs were beveled for full penetration weld. All four lugs were fitted using tack welds. These attachments were inspected for satisfactory fitting and released for welding in accordance with the approved weld procedure already in use in several other constructions in the yard. The qualified SMAW procedure specification (WPS) called for preheat temperature of 100°C and use of low hydrogen electrodes. The WPS was qualified on a 2.5-in.-thick plate that allowed the WPS to be used to weld up to an 8-in. thick plate. Qualified and experienced welders were assigned to the task of welding.

During the workday, three welds were completed and left to cool. Next morning, NDE inspector carried out the mandatory magnetic particle inspection on all three completed welds. All three pad-eye welds had developed toe cracks. The cracks were on the can side of the toe.

A brief investigation was carried out by review of the welding inspector’s log for compliance with the welding parameters, which was found to be in order. A discussion with welders revealed that the welds were completed at about 5:45 p.m. on the previous afternoon; after welding, they left the weld station and climbed down from the welding perch.

No clear explanation to the crack was established, especially since the WPS was successfully used on other jobs in the yard.

The focus was shifted from finding some lapse on part of the welding crew to more technical explanations to cracking. Welding inspector’s log was taken as the basis to calculate the cooling rate at the given condition, which is given in the following table as “At qualified WPS Preheat.” It may be noted that the relative wall thickness (τ) is above 0.9 for both 55-mm and 30-mm wall sections. It was established that a thick wall condition exists. The calculated cooling rate at the two welding speeds and hypothetical preheat temperatures of 300°C and 250°C ranged from 8.85°C/s to 19.12°C/s.

It was obvious that, at this level, the cooling rate of the weld was very fast, which had caused increased hardness at the thickest section of the weldments. The increased residual stresses (combined with the increased hardness) was exceeded by the cooling stress exerted causing the weld in HAZ to crack. The hardest points at the toe of the weld meant the thicker section was fastest to cool.

As an attempt to find a suitable cooling rate of below 6°C/s, a calculation was carried out with preheat temperature of 300°C on 55-mm can section and 250°C on 30-mm-thick pad-eye section. It was noted that thick wall conditions still exist as the calculated τ values are 1.64 and 1.2, respectively, and the resulting minimum cooling rate R is 8.85°C/s and 12.75°C/s, respectively. These cooling rates are faster than the desired 6°C/s or slower. To further reduce the cooling rate, the preheat temperature would require to be increased. Apart from the metallurgical factor, this was neither practical nor possible as it would restrict good performance from welders as well as logistic issues associated with precise control of temperature.

It was established that it was not possible to control the formation of hard martensite in the current welding conditions. However, it was possible to control the cooling rate by additional measures like either local stress relief or by wrapping the weldments with a heat insulator to allow slow cooling.

A set of two new procedures were qualified to supplement the existing WPS, with preheat temperature increased to 200°C. The preheat method was also changed from rose-bud propane torches to wrap-around electric heating pads. Two postwelding cooling control options were considered.

I. Immediately upon completion of the weld, the weld and the area surrounding the weld was to be heated to 450°C by heating pads. Upon reaching 400°C, the temperature was held for an hour then gradually reduced at the rate not exceeding 150°C per hour. As the temperature fell to 150°C, the weld was allowed to cool overnight wrapped in insulating blankets in a very controlled manner.

II. After welding, the weld was put on stress relief PWHT in which the weld area and adjoining material was heated to 650°C, held at that temperature for 4 h, and then allowed to cool slowly.

All regular tests associated with WPS qualification were carried out including hardness test on the weld and HAZ, and then on cross-section of the weld and HAZ. Hardness on both test specimens is given in the following table.

	Hardness on weld surface Vickers	**Macrosection hardness $V_{10\ Kg}$**		
Weld type	**Weld**	**Weld**	**HAZ**	**Microstructure**
Heated to 400°C	242, 239, 210	Cap$^{+1.5\ mm}$: 188, 169, 173 Mid: 169, 174, 170 Root$^{+1.5\ mm}$: 181, 175, 168	Cap$^{+1.5\ mm}$: 201, 210, 213 Mid: 172, 166, 171 Root$^{+1.5\ mm}$: 177, 172, 181	Pearlite and islands of tampered martensite

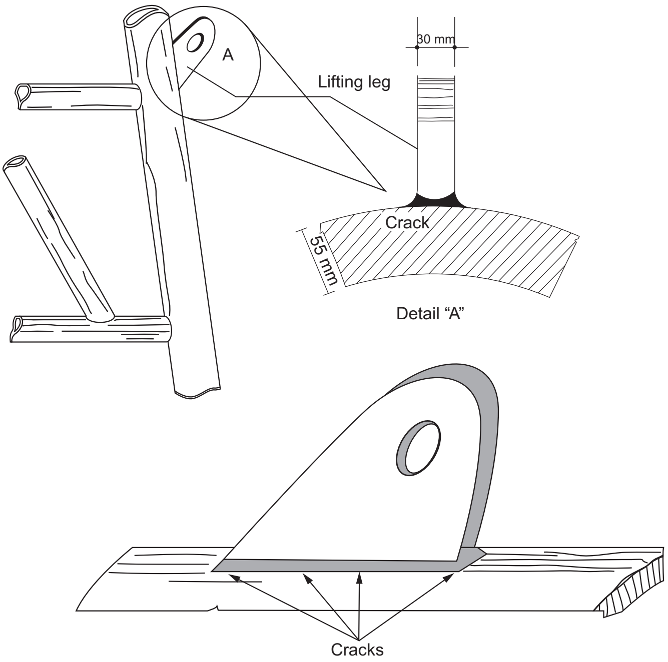
Stress relived at 650°C	239, 232, 236	Cap$^{+1.5\ \mathrm{mm}}$: : 185, 176, 177 Mid: 176, 164, 178 Root$^{+1.5\ \mathrm{mm}}$: 185,179, 181	Cap$^{+1.5\ \mathrm{mm}}$: : 200, 198, 209 Mid: 170, 172, 168 Root$^{+1.5\ \mathrm{mm}}$: 189, 183, 191	Pearlite and islands of tampered martensite

The microexamination of the weld cross-section was also reviewed; some islands of tempered martensite structure were noted in both specimens.

Both versions of postweld cooling control methods resulted in acceptable hardness and microstructure in weld that were able to reduce the possibility of postweld cracks. The option of choosing one of them was of fabrication convenience and logistics of the yard.

Volt	**I (A)**	**S (mm/s)**			**Process efficiency**	**Heat input (J/mm)**	H_{net}
24	230	4			0.9	1380.00	1242.00
24	230	6			0.9	920	828
Pc	To	Tc	TC-To	h	Tau (τ)		
0.0044	300	550	250	55	1.64	At Maximum Pre heat	
0.0044	250	550	300	30	1.20	At Maximum Pre heat	
0.0044	100	550	450	55	2.20	At qualified WPS Pre heat	
0.0044	100	550	450	30	1.47	At qualified WPS Pre heat	
Cooling rate calculation for relative thick (τ) wall condition as indicated.							
$\prod$	***k***				***Cooling rate (R °C) at Tc − To***	***Cooling rate (R°C) at Tc − To***	
3.1416	0.028				8.85	13.28	
					12.75	19.12	
Cooling rate calculation if relative thin wall conditions was $\tau \leq 0.6$							
$\prod$	***k***				***Cooling rate (R °C) at Tc − To***	***Cooling rate (R°C) at Tc − To***	
3.1416	0.028				23.72	53.37	
					12.19	27.44	

In the above, calculations using two different values for To and two different values of H_{net} does not give the desired cooling rate of ≤6°C/s. This will require that a postweld heat treatment is considered.



Postweld heat treatment (PWHT)

For some material, preheat alone is not sufficient to restore the properties. In such cases, after a weld is made, postweld heat treatment (PWHT) may be required to alter the unusual structure and properties produced by the rapid cooling associated with the welding process. PWHT is carried out to soften the weld zone (annealing) or to reduce hardening. The tempering operations can be performed to obtain weld zone properties similar to those in the base metal.

The metallographic microscope allows visual examination of the microstructural changes produced by the thermal effects of the welding operation.

The metallurgical factors important for controlling two important features of a weld joint are:

1. The composition and soundness of the weld metal
2. The microstructure of the weld metal and heat-affected zone of the base metal

Most welding processes apply heat to the work-pieces, and some of the metal in the joint area is melted. In terms of metal properties, the harmful effects of applying heat for welding outnumber the benefits. By controlling the heating and cooling cycles, it is possible to minimize the undesirable effects.

The welding process generates unusual combinations of time and temperature gradient; the temperature changes during welding are wider and more abrupt than in any other metallurgical process. The options of working and heat treatment to restore optimum properties are usually restricted in the case of welded structures, also called weldments.

The following are important points to consider when evaluating the thermal effects of welding:

- Rate of heating
- Length of time at temperature
- Maximum temperature
- Rate of cooling
- Cooling endpoint

As described before, factors like high stress or higher hardness associated with various grades of steel may require PWHT to make the weldments suitable for the designed service conditions. Such steels would require an additional PWHT. The PWHT for steels are often limited to heating to steel's **lower transformation** temperature, i.e., below the austenite start range below 723°C (1333°F) and cooling slowly. The stress reliving is aimed at reducing stresses by tempering few martensites that might have developed during fabrication welding.

The low alloy steels have their **lower transformation** temperature slightly above 723°C (1333°F), and specific care must be taken to determine the specific **lower transformation** temperature for the specific steel.

Other steels of higher strength and alloying elements may require additional or different heat treatments. Some of them are annealing, normalizing, quenching, and tempering. Various heat treatments are discussed in more detail in later chapters of this book.

Heat and time in welding

Heat will move from one area to another whenever there is a difference in temperature. Heat transfer occurs in three ways, as discussed at the beginning of this chapter, where we discussed heat flow and transfer of heat by conduction, convection, and radiation processes.

The difference in temperature per unit distance is called the temperature gradient. Welding involves very steep temperature gradients between the heat source and within the work-piece itself. The primary mode of heat transfer in welding is through conduction, however all three modes are involved.

Heat input

Relative to the overall volume and area of the work, the area and volume of the heat-affected zone in weldments is very small. To a significant degree, this is effectively controlled by the heat input. The magnitude of the rate of input energy, which is the product of arc efficiency and per-unit energy produced by the given welding process, expressed in watts, the distribution of heat input and the travel speed of the weld are the three variables that determine the heat input in any weld.

Energy distribution

The density of energy distribution of the heat on the surface of the work is an important factor in heat distribution. The weld and HAZ are formed within this heat distribution range and influence the formation of size and shape of the weld and HAZ. The weld thermal cycle in the close proximity of the weld and HAZ are of no significance for some materials like plain low carbons steel. In such situations, the heat input can be treated as a concentrated heat source, and heat input and weld travel speed are sufficient to determine the thermal cycle.

For an arcp-welding process, the deposition of heat is a distribution of heat flux on the surface of the weldments. An assumption is made that the heat of the arc is applied at an instant, and then the distribution of heat flux can be mathematically modeled at any point from the center of the arc. This is discussed in detail in the chapter discussing the physics of welding.

Rate of heating

The rate of heating of a work-piece that is being welded depends on how hot the heat source is and how efficiently the heat is transferred to the work. A higher temperature at the source means a steeper temperature gradient between it and the work; thus, the heating rate should be faster.

To illustrate the point, let us consider three welding processes using different sources to generate heat.

In oxyfuel welding, the heat is generated in the flame, and the gas molecules transfer their thermal energy to the metal. In arc welding, much higher heating rates are encountered. The arc temperature is much higher than that of an oxyacetylene flame. In addition, the arc is kept in intimate contact with the base metal, so there is efficient transfer of the heat.

In electric resistance welding, the metal itself is the heat source. Because most of the heat is generated at the contacting work surfaces, there is no effective transfer of heat, and a very high heating rate is obtained.

Maximum temperature

More heat is required to melt a given amount of metal than would appear from the mass of metal involved, because once the temperature is raised in one spot, it spreads and rises the temperature of all adjacent regions. So the heat of welding must be sufficient to not only melt the metal required for welding but also to heat the surrounding metal. Slower heat input rates result in greater amounts of heat required above the amount necessary to just melt the metal.

Heat generation and temperature distribution—Practical application

The physics of heat generation is discussed earlier. The following is the practical application of those principles in a real work situation. In arc welding, some of the heating of the material occurs through resistance to the passage of current through the material as it returns via the ground connection, but the arc produces a majority of the heat for welding.

The heat output of an arc is approximately equal to:

(Arc voltage) × (Arc current) × (Time in seconds that the arc burns-called Arc-Time)

For example, a covered electrode arc operating at 35 V and 150 A for a second liberates

$35 \times 150 = 5250$ joules every second.

This is equivalent to melting 0.02 pounds of steel in a second.

The energy output that enters the metal ranges from 20% to 85%; this depends on other welding conditions, such as travel speed. (Refer to the table giving the arc efficiency of various welding processes.)

Because metals are good heat conductors, the atoms in metal pass heat along to neighboring atoms very readily. The temperature distribution is actually occurring over a cross-section that is constantly changing as the heat source moves along the weld.

Time at temperature

The length of time at a maximum temperature depends on maintaining an even balance between heat input and heat loss. In most welding operations, this balance exists for only a very short period of time.

Usually, the temperature in a local area rises to the maximum and almost immediately begins to fall. It is this very rapid thermal cycling that accounts for the unusual aspects of a HAZ.

Cooling rates

In welding, the cooling rates are even more important than the rate of heating. We have discussed this subject in detail in previous pages of this section. Three features of the weld have the most profound effect on cooling rate:

1. The weld nugget acts as a heat source.
2. The mass of the base metal represents a heat sink.
3. The base metal temperature establishes the initial temperature gradient.

High-current, high-speed welds cool more slowly than low-current, low-speed welds. Increased heat input results in slower cooling rates if other factors are held constant.

Base metal mass

The mass of metal in the work-piece, previously deposited weld metal, fixtures, chill bars, etc. all act as heat sinks around the weld nugget.

Even with the same plate thickness, the mass of metal around the weld bead can be changed by depositing the bead on the edge of the plate or at an angle between two plates. The heat supplied to the edge bead can only flow in one direction, whereas the heat in the fillet weld will flow into both plates.

Only the volume of metal within a 3-in. radius of the weld affects the cooling rate through the important temperature ranges. Base metal that is further away only affects the cooling rate through low temperature levels.

In this context, it may be appropriate to discuss a very important subject relating to the arc strike outside the weld grove. Arc strikes are not desired, as they cause immense damage to the material due to the high cooling gradient because of a low area of heat relative to the large area of the base metal. This causes the heat to dissipate quickly and form hard martensite, which often is the cause of failure. The effect of arc strike can be determined using the same principles as discussed in the rate of cooling and preheat determination. The temperature raised by an arc strike can be determined by the following modified equation:

$$\mathrm{T} = \mathrm{To} + \left\{ 2\mathrm{Q}/p\mathrm{C}\,(4\eta\,\mathrm{at})^{1.5} \right\} - \mathrm{Exp}\left[-\mathrm{R}^2/4\,\mathrm{at} \right]$$

where:

T = Local Temperature raised by arc strike
To = Initial temperature
R = 0
Q = Net heat input = $\mathrm{qt}_{\mathrm{weld}} = \eta\ \mathrm{E\ I\ t}_{\mathrm{weld}}$
q = Net arc power
$\mathrm{t}_{\mathrm{weld}}$ = Duration of arc strike (weld time)
η = Arc efficiency
E = Arc voltage
I = Arc current
V = Welding speed
a = Area affected by strike/second (mm^2/s)

Selection of consumable electrode or wire for welding: Case Study 2

Choice of welding filler wires or electrode is an important step in getting a compatible weld material. Apart from the chemical and mechanical priorities, comparing to match material with the available options is not good enough. Factors like availability of welding processes, follow-up machining, heat treatment, specific working condition, or method and availability of inspection, etc. may present specific challenges. An educated compromise is often a necessity to derive best possible results. Following is a real-life case as an illustration to the point.

Background to the case

In one of the prominent pipeline projects consisting of 24-in.-diameter and 0.980-in. and 1.125-in. wall thickness API 5L X 80 (PSL2) grade of line pipe, the challenge was to balance the need of low defused hydrogen weld and ensure good weld penetration. The pipeline operator had reservations with the use of mechanized welding and insisted that only a manual or semiautomated process be used for welding pipes on this project.

Given this limitation, developing a suitable welding procedure was a challenge.

Contractors were comfortable with the use of an automatic welding process because it would ensure low hydrogen process and full penetration of the weld. However, in the given situation, the choice was to use SMAW process and cellulose electrode to ensure good penetration while keeping the diffused hydrogen in the weld within acceptable limits of less than 4 mL/100 g of weld metal.

Pursuant to these requirements, as a prebid condition, bidding contractors were asked to develop and qualify a procedure that would meet these conditions. Contractors submitted their proposed welding procedures, and two procedures were considered viable.

1. SMAW cellulose electrode for root pass to ensure good penetration and then follow-up with either FCAW or GMAW process.
2. The second contractor proposed two versions of the procedure; in both of them, root and hot passes were welded with SMAW cellulose electrode and followed one with FCAW and second with GMAW process.

Along with these WPS coupons, the contractors were also asked to weld a root and hot pass on a coupon with cellulose electrode. This weld was used as a reference to establish the level of dissolved hydrogen in the weld.

A preheat temperature of 120°C was specified and maintained for all welds. Contractors completed all welds. Welding was not stopped until completed except for normal cleaning and grinding as part of the welding process. This was to allow as much time and temperature as possible for the hydrogen from cellulose dissolved in the weld metal to escape through the successive low hydrogen weld metal passes.

Among several other standard tests involved with welding procedure qualification, one more test was added to evaluate the amount of dissolved hydrogen in the weld, especially in the sampling from the root and hot passes regions.

The Testing:

Samples from all the welds were sent to a laboratory to analyze for diffusible hydrogen in the weld using methods described in AWS A 4. 3.

Cellulose weld metal testing

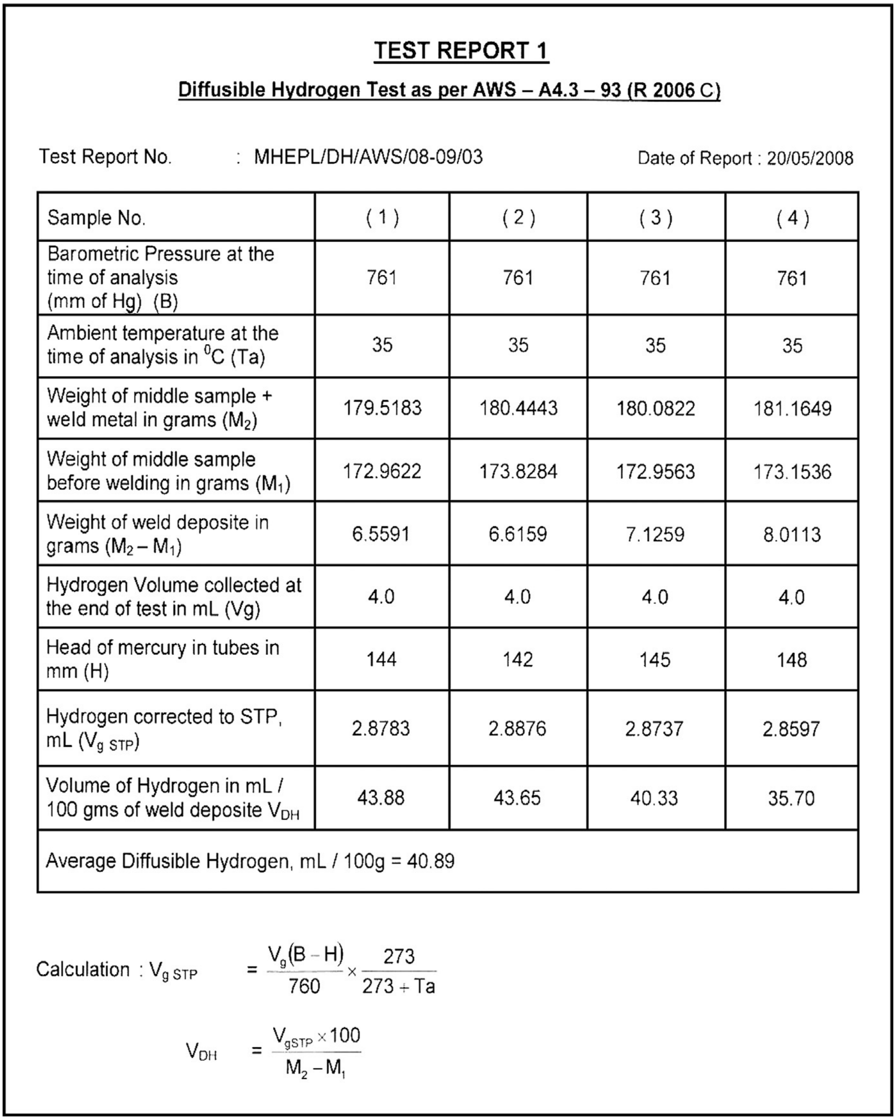
The laboratory was instructed to first test the root and hot pass weld metal from cellulose electrodes. Four specimens were cut and analyzed for the diffused hydrogen level, according to AWS A 4.3 (Rev. 2006). Standard mercury displacement method was used for analysis.

The temperature of bath was maintained at 45°C ± 1°C. Seventy-two hours were allowed to evolve the diffused hydrogen. The laboratory reported that all the cellulose electrode root and hot pass-only weld contained hydrogen in excess of 16 mL of diffusible hydrogen per 100 g of weld metal.

The average of the three specimens tested was 40.89 mL diffusible hydrogen per 100 g of weld metal. The report makes it clear that the welds in question have diffusible hydrogen in excess of the acceptable limit of 4 mL/100 g as specified for the rest of the welds in the main pipeline. The reported average diffusible hydrogen in the weld metal is far more than 4 mL/100 g maximum that the engineering team could accept as a low hydrogen weld. This was used as a reference to evaluate the rest of the welds. (See the test report.)

The specimen from weld coupons completed with cellulose root and hot-pass plus low hydrogen process fill and cap welds were also similarly tested according to AWS A 4.3 mercury displacement method.

The resulting diffusible hydrogen in each weld was recorded between 3.38 mL/100 g to 4.95 mL/100 g of weld metal. (See the test report.)



TEST REPORT 1

Diffusible Hydrogen Test as per AWS – A4.3 – 93 (R 2006 C)

Test Report No. : MHEPL/DH/AWS/08-09/03 Date of Report : 20/05/2008

Sample No.	(1)	(2)	(3)	(4)
Barometric Pressure at the time of analysis (mm of Hg) (B)	761	761	761	761
Ambient temperature at the time of analysis in ^{0}C (Ta)	35	35	35	35
Weight of middle sample + weld metal in grams (M_2)	179.5183	180.4443	180.0822	181.1649
Weight of middle sample before welding in grams (M_1)	172.9622	173.8284	172.9563	173.1536
Weight of weld deposite in grams ($M_2 - M_1$)	6.5591	6.6159	7.1259	8.0113
Hydrogen Volume collected at the end of test in mL (Vg)	4.0	4.0	4.0	4.0
Head of mercury in tubes in mm (H)	144	142	145	148
Hydrogen corrected to STP, mL ($V_{g\ STP}$)	2.8783	2.8876	2.8737	2.8597
Volume of Hydrogen in mL / 100 gms of weld deposite V_{DH}	43.88	43.65	40.33	35.70
Average Diffusible Hydrogen, mL / 100g = 40.89				

Calculation : $$V_{g\ STP} = \frac{V_g(B - H)}{760} \times \frac{273}{273 + Ta}$$

$$V_{DH} = \frac{V_{gSTP} \times 100}{M_2 - M_1}$$

	Specimen			
	Contractor—A		**Contractor—B**	
Root and Hot pass	**SMAW cellulose**	**SMAW cellulose**	**SMAW cellulose**	**SMAW cellulose**
Fill and Cap	**FCAW**	**GMAW**	**FCAW**	**GMAW**
Test Parameters				
Barometric Pressure at the time of the test (mm of Hg) (B)	761	761	761	761
Ambient temperature at the time of analysis in °C (Ta)	32	32	32	32
Weight of the sample with weld in grams (M2)	158.441	159.068	156.989	160.002
Weight of the sample before weld in grams (M1)	153.343	154.876	152.385	154.937
Weight of the weld deposit in grams (M2-M1)	5.098	4.192	4.604	5.065
Volume of hydrogen collected at the end of the test in mL (Vg)	0.26	0.19	0.28	0.21
Head of mercury in tubes in mm (H)	142	142	142	142
B-H	619	619	619	619
273-ta	205	205	205	205
Volume of hydrogen corrected to STP in mL (VgSTP)	0.212	0.155	0.228	0.171
Volume of dissolved hydrogen in ml/100 g of weld deposited (VDH)	4.15	3.69	4.95	3.38

Welding and joining processes

3

As we have learned from the introduction of this section, many welding processes require application of heat and/or pressure to produce a suitable bond between the two parts being joined.

The most common, conventional, and commercially practiced weld processes are listed in Table 2-3-1. This table describes in general the materials that can be welded or joined using a specific process. It may be noted that the processes have their limitations in relation to the material thickness, and cost analysis may not allow for a process to be used on a specific application.

The selection of a suitable welding consumable (electrode or wire) is also an important factor in producing suitable weldments. Selection of a consumable electrode for a job is dependent on several factors: the intended engineering stress on the weld is one of them, as well as the welding process being used for the work. Great care is required in this process, and some engineering and commercial compromises are necessary to arrive at a suitable selection. One example of these compromises and challenges is discussed in the case study.

The American Welding Society's (AWS) standard terms given in the following table are used to describe these welding processes. It may be noted that some of these generic processes have several variants, and they are used in industries with their new names and acronyms such as surface tension transfer (STT), which is a gas metal arc welding (GMAW) process; high frequency welding (HFW) and induction welding; seam welding; spot welding; and projection welding, which all variants of electric resistance welding (RW). Argon arc welding and Heli-Arc welding are a part of GTAW process. Some of these additional terms are not yet adopted as standard terms by the AWS as an independent welding process but rather as part of the generic nomenclature.

1.	SAW	Submerged Arc Welding
2.	SMAW	Shielded Metal Arc Welding
3.	GMAW	Gas Metal Arc Welding
4.	FCAW	Flux Cored Arc Welding
5.	GTAW	Gas Tungsten Arc Welding
6.	PAW	Plasma Arc Welding
7.	ESW	Electroslag Welding
8.	EGW	Electrogas Welding
9.	RW	Resistance Welding (EW is also used in some documents)
10.	OFW	Oxyfuel Gas Welding
11.	DFW	Diffusion Welding
12.	FRW	Friction Welding
13.	EBW	Electron-Beam Welding
14.	LBW	Laser-Beam Welding
15.	B	Brazing
16.	S	Soldering

Applied Welding Engineering. https://doi.org/10.1016/B978-0-12-821348-3.00015-X

Table 2-3-1 Master chart of welding and joining processes indicates general limits of joining/welding processes that apply to the material listed in left column.

Material	**Welding processes**														**Other joining processes**	
	SMAW	**SAW**	**GMAW**	**FCAW**	**GTAW**	**PAW**	**ESW**	**EGW**	**RW**	**OFW**	**DFW**	**FRW**	**EBW**	**LBW**	**B**	**S**
Carbon Steel	x	x	x	x	x		x	x	x	x		x	x	X	x	x
Low Alloy Steel	x	x	x	x	x		x		x	x		x	x	X	x	x
Stainless Steel	x	x	x	x	x		x		x	x	x	x	x	X	x	x
Cast Iron	x	x	x	x						x					x	x
Nickel and Alloys	x	x	x		x	x	x		x	x					x	x
Aluminum and Alloys	x		x		x	x	x	x	x	x	x	x	x	X	x	x
Titanium and Alloys			x		x	x			x		x	x	x	x	x	
Copper and Alloys			x		x	x						x	x		x	x
Magnesium and Alloys			x		x				x			x	x	x	x	
Refractory Alloys			x		x	x			x				x		x	

The term *arc welding* is used to classify a group of processes that use electric arc as a source of heat to melt and join metals.

As noted from the earlier discussion and the table, a large number of welding processes use electric arc as a source of heat for fusion. An electric arc consists of a relatively high-current discharge sustained through a thermally ionized gaseous column called plasma.

The power of an arc may be expressed in electrical units as the product of current passing through the arc and the voltage drop across the arc. In a typical example, 350 A at 22 V will dissipate 7700 W of power. This will generate heat energy of about 7700 J/s or about 7.30 Btu/s. However, as discussed an earlier part of this book, it may be noted that not all the heat generated can be effectively utilized for welding. As heat loss occurs, the effective heat is significantly lower than the generated heat as calculated earlier. This general efficiency of an arc is called" "arc efficiency." The arc efficiency of some very common processes is given in Table 2-3-2. A detailed discussion of power sources for various arc-welding processes will be found in the next chapter.

Arc efficiency of a welding process is an important variable that should be considered in determining the effect of heat on the weld and heat-affected zone. Table 2-3-2 lists the arc-efficiency range and mean values of some of the most commonly used processes.

Note: The Watt (W) for direct current (DC) is calculated as:

$$\mathrm{W} = \mathrm{EI} \qquad [1]$$

For alternating current (AC), the relationship is not straight; the phase angle (θ) between the sinusoidal current and voltage is taken into the equation. This relation is expressed as Cos θ, and it is called the "power factor." Thus, for AC, the power (W) will be:

Table 2-3-2 Arc efficiency.

	Process	**Arc efficiency**
1	GTAW	Low
2	SMAW	Intermediate
3	SAW	High
	Arc efficiency factor η	
Welding process	**Range**	**Mean**
Submerged Arc Welding	0.91–0.99	0.95
Shielded Metal Arc Welding	0.66–0.85	0.80
Gas Metal Arc Welding (CO_2 Steel)	0.75–0.93	0.85
Gas Metal Arc Welding (Ar Steel)	0.66–0.70	0.70
Gas Tungsten Arc Welding (Ar Steel)	0.25–0.75	0.40
Gas Tungsten Arc Welding (He Aluminum)	0.55–0.80	0.60
Gas Tungsten Arc Welding (Ar Aluminum)	0.22–0.46	0.40

$$W = EI \cos \theta \qquad [2]$$

In general, the arc-welding process can be described as the process where a welding arc is struck between the work-piece and the tip of the electrode. The electrode may or may not be consumed in the joining (welding) process.

The nonconsumable electrodes are either carbon or tungsten. The arc-welding processes may provide the forward movement to electrodes either by manual or mechanical operations.

Similarly the filler material may be fed into the weld pool either by manual or mechanical means. In case all these activities are manual, the process is termed as a *manual process*; conversely, if all the process activity is mechanical, the process is called *automatic*. There exists the possibility of mixing mechanical and manual operations, so in that case the process is called *semiautomatic*, and some specifications have called them a *mechanized process*. A majority of semiautomated processes have taken away the wire-feed from manual control and mechanized it. (See the semiautomatic welding of pipeline girth weld.)

Mechanization of process is motivated by the use of both higher current and feed speed in some processes, which are interdependent.

Arc-welding power supply units reduce the high line voltage to a suitable output voltage range, from 20 to 80 V. Transformers, solid-state inverters, or motor-generators are used as power sources. The same device then supplies the high welding current (30–1500 A) in either AC, DC, or both.

Constant-current machines adjust the load current to maintain a static volt-amp curve that tends to produce a relatively constant load current. The load voltage is responsive to the electrode-to-work distance. These machines are usually used for manual welding with a covered or tungsten electrode to minimize the inevitable variations in arc length.

Constant-voltage machines adjust the load current to maintain a relatively constant load voltage. The load current is responsive to the rate at which a consumable electrode is fed into the arc. This self-regulating machine stabilizes the arc length for wire welding.

In the following section, we shall discuss some of the commonly used welding processes and their silent features.

Shielded metal arc welding (SMAW)

Process fundamentals

Shielded metal arc welding (SMAW) process is one of the earliest arc-welding processes and a versatile one for welding ferrous and several nonferrous metals. The process is also called manual metal arc (MMA) welding process in the United Kingdom and some European countries. The process uses covered electrodes. An electrode consists of a core metallic wire covered with silicate binders and other material that may include fluorides, carbonates, oxides, metal alloys, and cellulose. The cover is extruded over the wire. The covering is then dried in an oven. The covering has several roles to play.

1. It works as an arc stabilizer,
2. It provides shielding from atmospheric contamination during molten state by evolving gases and during solidification by covering the weld metal with slag.
3. It provides scavengers, deoxidizers, and fluxing agents to cleanse the weld and prevent excessive grain growth in the weld metal.
4. It provides a slag blanket to protect the hot weld metal from the air and enhance the mechanical properties, bead shape, and surface cleanliness of the weld metal.
5. It is also a source of alloying elements to produce compatible weld metal.

How the process works

The bare metal end of the electrode is clamped in the electrode-holder, which is connected to the power source; the other lead of the power source is connected to the work terminal. The arc is struck by bringing the electrode into contact with the work surface and then immediately pulling them apart about 2–3 mm (about 0.08–0.12 in.), thus ionizing the gas between the two electrical ends. The resulting arc generates heat to melt the work metal and the metal electrode. The coalescence of metals is produced by heat from an electric arc maintained between the tip of the covered electrode and the surface of the base metal in the joint being welded.

Covered electrodes used in SMAW process

The AWS classifies electrodes on the basis of chemical composition of their undiluted weld metal, mechanical properties, or both. Welding current and position are also indicated.

Carbon steel electrodes are included in AWS Specification A5.1. There are two strength levels: 60 and 70 ksi. An example of electrode designation system is E6010, which is explained in the following text. Some of the other commonly used electrodes are E7011, E7015, E7018, and E7024. For example, in an electrode designated as E6010, the letters and numbers have the following explanations:

- The letter E designates it’s an electrode.
- The number 60 signifies that the tensile strength of the deposited weld metal is a minimum of 60,000 psi.
- The second-to-last digit (1) represents the welding position the electrode is suitable for use (1 = all positions).
- The last digit (0) refers to the covering type and current type; in this case, 0 indicates the covering is cellulose, and the electrode is good for all positions of welding.

Low-alloy steel electrodes are included in AWS Specification A5.5. Their numbering system is similar to that used for carbon steel electrodes. A letter or letter/

number combination suffix is added to indicate the alloy content (E7010-A1, E8016-C2). Weld metal strengths of alloy steel electrodes range from 70 to 120 ksi minimum tensile strength. The AWS specifications use suffixes at the end of the electrode designation to classify the alloying elements; from time to time, AWS reviews new developments and adds or withdraws these designations as required. The following are some of the most common suffixes and their intended meanings.

Suffix	Meaning of the suffix in carbon and alloy steel SMAW electrodes
A_1	Contains 0.5% Molybdenum (Mo)
B_1	Contains 0.5% Chromium (Cr) and 0.5% Mo
B_2	Contains 1.25% Cr and 0.5% Mo
B_3	Contains 2.25% Cr and 1% Mo
B_4	Contains 2% Cr and 0.5% Mo
B_5	Contains 0.5% Cr and 1% Mo
C_1	Contains 2.5% Nickel (Ni)
C_2	Contains 3.5% Mo
C_3	Contains 1% Ni, 0.15% Cr, and 0.35% Mo
D_1	Contains 1.75% Manganese (Mn) and 0.25% Mo
D_2	Contains 1.75% Manganese (Mn) and 0.45% Mo
G	0.5% Ni, 0.3% Cr, 0.2% Mo, 0.1% V, and 1% Mn (only one of these elements has to meet the requirement to qualify as "G" electrode)
L	Controlled elements (for example, low carbon)
M	Meets military requirements
HZ	Meets weld metal-diffusible hydrogen requirements H1, up to 15 mL/100 g of weld metal H2, up to 10 mL/100 g of weld metal H3, up to 5 mL/100 g of weld metal H4, $\leq$5 mL/100 g of weld metal
R	Meets absorbed moisture test requirements
Numerical	Numerical suffixes follow the previously listed and indicate the toughness properties of the weld metal

Electrode conditioning refers to the storage and handling of covered electrodes to maintain their optimum moisture content. Low-hydrogen electrodes such as E7018 must be maintained in a holding oven set at 150–300°F. Excessive moisture can cause porosity or lead to hydrogen cracking.

Cellulose electrodes (E6010, E6011) are not required to be conditioned; they do not operate properly if they dry out and should be stored in a clean, dry place rather than in an oven.

Corrosion-resistant steel electrodes are included in AWS Specification A5.4. Their classification is based on chemical composition, position of welding, and the type of welding current. For example, E310-15 is an electrode with nickel and chromium alloying suitable for use in all positions with DC current.

AWS specifications exist for nickel alloy, aluminum alloy, and copper alloy electrodes as well as cast iron welding, hard-surfacing, and overlaying.

Table 2-3-3 Factors influencing joint design.

	Key factors influencing the joint design	Subfactors that cross-influence the selection
1	Material	Type, thickness
2	Welding process	
3	Weld design	Access to the weld from both sides or single side
4	Design demands of the completed weldments	Weld strength, weld esthetics, welds

Joint design and preparation

Although square groove joints are the most economical to prepare, the thickness is limited to about 6 mm (¼ in.). For thicker members, the edges must be prepared to a contour that will permit the arc to be directed to the point where the weld metal must be deposited. Standard 30-degree bevel, J-groove, and U-groove joints are desirable for intermediate thick sections as they allow access to the root with the least amount of filler metal required. Higher thicknesses may have composite and double bevel preparations for welding by SMAW process. The selection of the type of joint preparation is a function of several factors as described in Table 2-3-3.

Fillet welds require little or no preparation and may be combined with groove welds. Minimum stress concentration at the toes is obtained with concave fillets.

When full penetration joints are required and welding must be performed from one side only, backing bars may be used to provide a retaining surface for the first layer of weld metal to be deposited. When there is access to the other side, a backing weld may be made and ground back to sound metal, and rest of the weld may be completed from the second side.

Gas tungsten arc welding

Process description

Gas tungsten arc welding (GTAW) uses a nonconsumable tungsten electrode that must be shielded with an inert gas. The arc is established between the tip of the electrode and works to melt the metal being welded. The consumable filler metal is added either manually or by some mechanized process. The inert gas shielding protects the molten metal, which is cooling, and it also provides the required arc characteristics.

The process may use direct current (DC), with positive or negative polarity, attached to the tungsten electrode, although in most applications the electrode is attached to the negative polarity. Alternative current (AC) is also used to produce different effects on the welding.

Argon and helium are the two inert gases used for this process. Choice of gas and type of current and polarity depends on the type of material and quality of weld desired, for example, use of helium gas will result in deeper penetration, and if helium gas is used with DC current, then the process would provide the deepest penetration of the weld.

Use of AC current with argon shielding helps remove oxides from materials that have passivation films like aluminum and stainless steels.

The process uses constant-current welding power. High frequency oscillation is generally provided for AC power sources. High frequency attachments with a DC process allow for "no-touch" starting of the arc, a distinct advantage for producing high quality welds.

There are variations of the GTAW process that includes different types of automation, which may also include improved deposition rate. These systems are in the market with different trade names from a variety of manufacturers. In the automation field, the variants could be a system used to weld pipe girth weld, in which the unit that holds the weld with a tungsten electrode, wire feed unit, and gas supply connection are often mounted in one unit. That unit rotates on a rack-and-pinion mechanism around the weld. The early use of these systems included welding in tight spaces such as boiler tubes and tube sheet welding, etc. However, more advance systems are now in use for other orbital welding, such as pipelines, and in more adopted forms, such as cladding of valve and pump internals, etc.

For the increase in deposition rates, various options are available. There can be multiple head wire feed units that feed more than one wire to increase the deposition rate, but more often seen option is the hot wire process. The hot wire option uses an independent source to heat the wire to a level below its melting temperature just before it is fed into the molten pool created by the tungsten electrode. The process allows for a limit on arc energy utilization.

The pulsed version of GTAW power sources often use a DC pulsed power source. These are often specialized power source applications of a proprietary nature designed for automatic girth welders or cladding of special parts where the efficiency of the process is of higher demand. The pulsed current system alternatively outputs high and low currents at a nominal value of about 6 Hz. Normally the natural frequency of steel is considered to be between 6 and 7 Hz depending on the type and grade of steel. In a pulsed current system, the current is synchronized with the rate of wire feed and voltage control of the machine. During the high current state, the pulsed current melts the metal and creates a molten pool in which the filler wire is added to accomplish the weld. In the lower current phase of pulse, the back-low ground current gives it time to cool and allows control over weld pool management. When more variations are added, like effect of oscillation or heating current, then synchronization of pulse is required, and this can bring down the frequency to very low numbers like 1 or 2 pulse per second. In the other variable, like thickness of material where a higher current is required to heat and melt, the demand on the time scale of the background current is critical. It is required that the time of the high current phase is matched with the lower cooling current phase.

Because most of these are newer developments and are patent protected, more detail on any of the specific equipment can be obtained from specific equipment or system manufacturers.

Process advantages and limitations

The GTAW process produces superior quality welds free from most defects. The welds are free from slag inclusions and, if properly maintained, free from any inclusions including tungsten inclusion. It is also free of spatter process. The process can be used with or without filler metal (autogenous) as required. It allows excellent control of the root pass weld penetration. It can use relatively inexpensive power supplies. It allows precise control of welding variables. It can be used to weld almost all metals. It allows independent control of the heat source and filler metal additions.

Deposition rates for this process are low. Compared with other processes, the welder requires more skill to be able to produce a quality weld. The weld area must be protected from wind and drafts to maintain the inert gas envelope over the weld zone. Tungsten inclusions can occur if the electrode is allowed to contact the weld pool. Contamination can occur if proper shielding is not maintained or if the filler metal or base metal is contaminated.

Electrodes

The function of the tungsten electrode is to serve as one of the electrical terminals for the arc that supplies the heat for welding. Tungsten has a melting point of 3420°C (6170°F). At high temperatures, it is thermionic and emits electrons. It is the cooling effect of the electrons boiling from its tip that prevents the tungsten electrode from melting.

The electrodes are classified according to purity and alloying elements; the classification is indicated by the color coding on the tips of the electrodes.

AWS Specification A5.12 classifies tungsten electrodes. EWP is pure tungsten. EWTh-2 is alloyed with ThO_2 to improve arc stability. EWZr-1 is alloyed with ZrO_2. Normally, straight polarity is used to provide cooling of the electrode.

The electrode tip configuration influences weld penetration and the weld bead. For DC welding, the tip should be ground to a specific angle with a truncated end. With AC welding, a hemispherical tip is used. Contamination of the tungsten electrode can occur when it touches either the molten pool or the heated filler metal. Improper gas shielding can cause oxidation.

Joint design

The five basic joints shown in Figure 2-3-1 and their variations may be used for welding most metals.

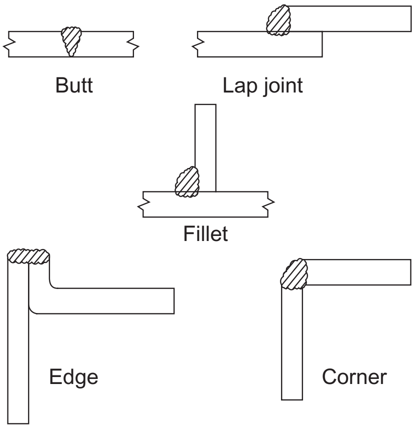


Figure 2-3-1 Five basic weld joints.

When designing a weld joint, care must be taken to ensure that there is enough room for proper accessibility for the welder to allow manipulation of the electrode holder to obtain adequate fusion of the groove face and addition of filler metal.

The cleanliness of tools used by fabricators and welders for joint preparation are important. Any contamination with abrasive particles or cutting fluids can cause weld defects. Both the filler metal and the base metal must be cleaned to remove all traces of oil, grease, shop dirt, paint, marking crayon, and rust or corrosion.

Gas metal arc welding

In the simplest version of its description, the GMAW process has traditional variants such as short circuit transfer, globular transfer, and spray transfer modes.

GMAW uses a continuous (solid wire) consumable electrode. The process is also referred to as a gas metal arc (GMA) process. The filler wire is fed by mechanical means, and a shielding gas is supplied through the handheld nozzle. If the process is fully automated, then the gas is supplied through nozzles mounted on the mechanized system. After initial settings by the operator, the process of wire feed is self-regulating.

The welding gun guides the feed of the consumable electrode and conducts the electrical current and shielding gas to the work. Energy is provided to establish and maintain the arc and melt the electrode as well as the base metal.

Metal transfer across the arc can occur in any of the three modes discussed in the following description.

Process description

As stated above in the introduction of the gas metal arc welding (GMAW) process, the continuous (solid wire) consumable electrode is fed into the weld by three modes.

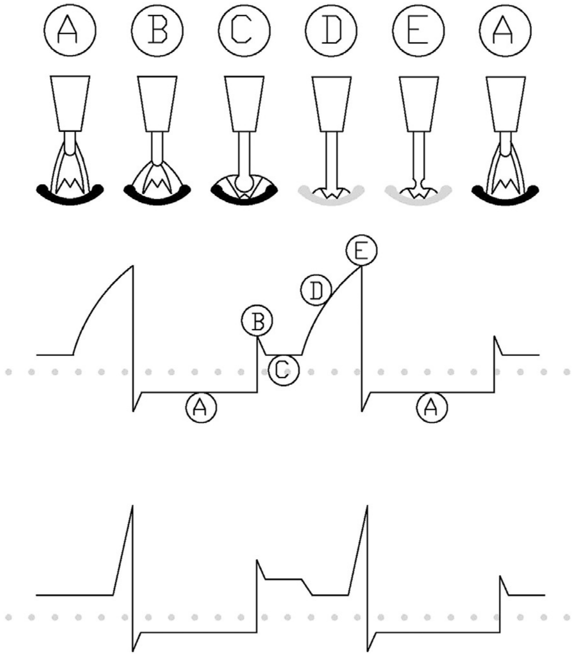


Figure 2-3-2 Short circuit transfer (arc-action and cycle).

The following is the description of three modes of metal transfer in the GMAW process.

1. **Short circuiting transfer** occurs in the lowest range of welding currents and electrode diameters. It produces a small, fast-freezing weld suited for joining thin sections, for welding out of position, and for bridging large root openings. The wire electrode actually contacts the weld pool at the rate of 20–200 times per second. Inductance is used in the power supply to control the amount of heat available before the short circuit occurs.

   The process in its present form can be used for welding thin sheets and/or positional welding where very precise control over the weld metal pool is required (Figure 2-3-2).
2. **Globular transfer** takes place when the current is relatively low with all kinds of shielding gas but always occurs with CO_2 and helium. Molten metal drop sizes are larger than the electrode diameter. Because the large drop is easily acted upon by gravity, welding is usually confined to a flat position.
3. **Spray transfer** produces a very stable spatter-free axial spray transfer when the current level is above the minimum transition current. The process can be used only in the flat and horizontal positions because the weld pool is large. Argon or argon-rich gases are required for this process. For welding aluminum, titanium, magnesium, and their alloys, the argon-helium mix gas is often used. For welding ferrous material, small amounts of oxygen or carbon dioxide is added to stabilize the arc and eliminate excessive spattering of material. A combination of 75% argon and 25% CO_2 gas is a common gas mix used for carbon steel welding; such gas mix and other variations are commercially available from gas suppliers. The electrical power used is DC, and the electrode is connected to the positive point of the power source.

These are definitions and descriptions of three basic types of GMAW metal transfer process. Although these types are still valid, their identities are a little blurred due to new developments in metal transfer techniques, resulting in a number of new names for specific variants of the welding process. Some of these newer variants are introduced in this chapter. It may be noted that newer variants are mostly proprietary in nature, are patent protected, and not many details can be easily obtained. In most cases, they are also designed to address a specific type of work requirement.

Electrode selection

The filler metal must produce a weld deposit that either closely matches the mechanical properties of the base metal or provides enhancement to the base metal property (such as corrosion resistance). The deposit must also be free of discontinuities.

AWS Specification A5.10 includes filler wires for aluminum and aluminum alloy welding. Similarly, A5.19 describes filler materials for magnesium, A5.6 for copper, A5.14 for nickel alloys, A5.16 for titanium alloys, A5.9 for austenitic stainless steels, and A5.18 for carbon steels.

Joint design

The deep penetration characteristic of spray transfer permits welding in joint preparation that has a smaller included angle, which is an advantage as it allows for reduced filler metal consumption and labor cost to complete the joint. But such weld joint preparation must be carefully evaluated for potential metallurgical problems arising due to the high depth-to-width ratio, which can lead to cracking of the weld.

Gas metal arc welding: Newer variants

Most of the new GMAW developments come with new names given by developers and manufacturers. These new variants and their specific methods of variations are often proprietary, patented, and specific to the task they intend accomplish. The details are guarded with utmost secrecy. These new developments are possible due to modern electronic devices installed in the welding machines that use innovative digital control and regulation concepts, including clock-pulse controls.

The changes have occurred in both short circuit arc transfer and spray arc, as well as in pulsed arc metal transfer modes. The following is a brief introduction to these developments.

The traditional short circuit transfer mode is described earlier, where transformers, rectifiers, and chokes are used as welding and welding control mechanisms. In these, the arc is extinguished when the droplets transfer into the weld pool. The limitation of the process is realized when the variations in joint design and positions occur, leading to changing conditions such as alteration in arc length and wire feed speed. Such changes result in arc instability and excessive spatter.

In new developments, this is addressed by inclusion of the switching frequency over 100 kHz in the welding machine system; this is also referred to as the frequency of the welding system. Modern systems use digital signal processors with computerized controls to regulate the current and voltage output. Such controls tend to compensate for variations in current and arc stability as limitations of the short circuit process discussed earlier.

This principle is utilized by various manufacturers with their own process-focused refinements and, as stated before, they all have their own new names. Names like cold metal transfer (CMT), ColdArc, ColdMIG, and STT etc., are all trade (brand) names using their own specific development and patented techniques.

These new developments broadly fall into two groups.

1. Short circuit arc with constant feed of wire and installation of trigger points in the voltage and current path.

   The advantage of this method is that it allows better control over energy input pressure on the weld pool, which helps reduction of spatter, and the joining process is very smooth. The trigger points are initiated to control the quick-changing wire feed. This also supports the metal detachment from the electrode wire process. The electrical energy is used for elimination of the short arc, as it can be reduced to a minimum. After the detachment of droplet, the wire feed direction is reversed to reignite the arc process. The control mechanism of retraction and forward motion of the wire feed allows good electrical contact and good stability of the process. These controls offer a very good welding process for welding with limited heat input and low deposition.

   In the AC versions of the short circuit arc process, the arc varies between negative and positive polarities. During the negative polarity, the wire is enveloped under the arc, and this leads to formation of a larger droplet. This is often the leading cause of low penetration, high deposition rate, and low heat input during this phase.
2. Short circuit arc with wire retraction during resignation of the arc process.

   In this process, the computer-controlled power supply can provide switching power.

   These systems have a quick-changing wire feed system in the torch that helps the detachment of droplets. In this short circuit arc process, the polarity changes to negative polarity, which gives a variable negative polarity. This allows for variations in heat input and the deposition rate to suit the job requirements (Figure 2-3-3).

The process combines application of lower current and smaller diameter wire while as stated in the introduction of short circuit metal transfer process, it is suitable for welding with precise weld metal pool control, for example, welding out of position welds and thin sections of sheet metal. It has one main disadvantage, which is high spatter level due to frequent fluctuation of the current and voltage cycle. This is associated with the squeezing of the droplet detachment stage of the pinch cycle.

To improve this and increase the efficiency of the process, better controls of the current cycle are included. Newer welding processes, as stated earlier, have addressed this issue through installed electronic regulation (either a software or hardware path is chosen) in their equipment. They approach the issue by developing digitally controlled power sources that gives them a distinct advantage on waveform control. Primarily, they all depend on the rapid reduction of the welding current just before the reignition stage, which allows a significant reduction in spatter, reduction in heat input, and all this allows welding of thinner sections and gap-bridging abilities.

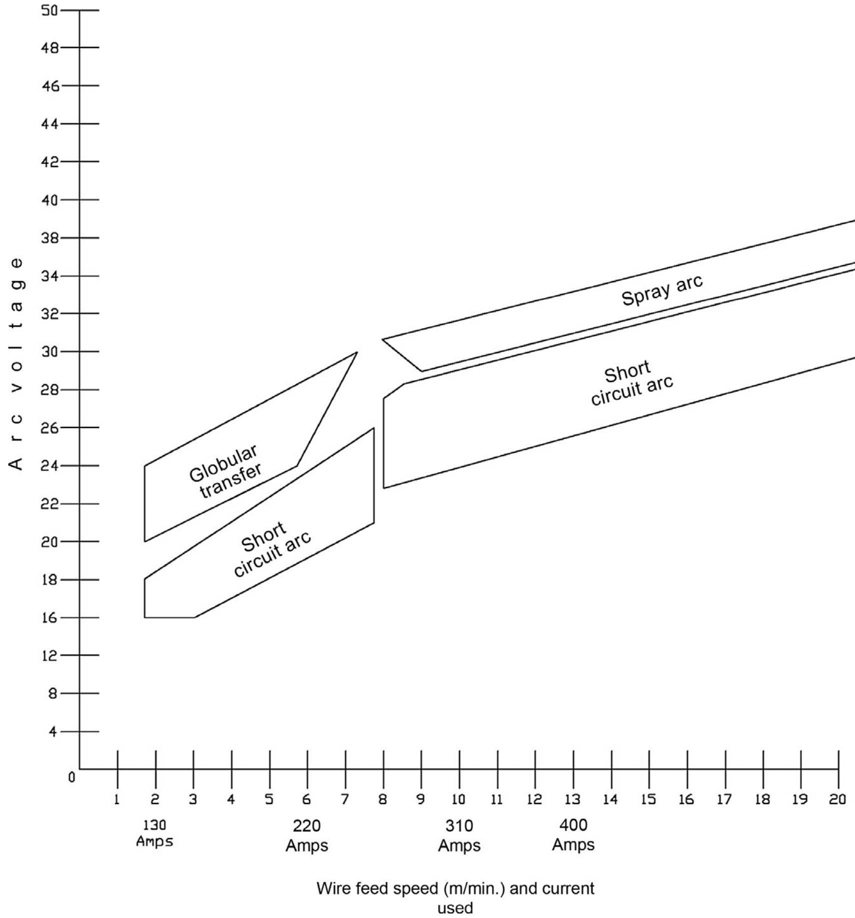


Figure 2-3-3 Metal transfer in short circuit GMAW process.

The pulse arc systems

As in the short arc modes discussed before, the pulsed arc mode also includes high switching power techniques that improve efficiency and gives more precise control on arc behavior. The control efficiency of the process is better due to the high frequency of the switching.

The system allows for an increased deposition rate; the pulse current can be adjusted to use short circuit mode droplet transfer mode, pulse current droplet detachment mode, or even multidroplet metal transfer mode.

The new system allows development of various strategies for modulation to achieve process stability. The background and pulse current phases can be controlled or modulated to reduce spatter in most stringent conditions such as short settings.

Various proprietary systems are in the market with these program modes.

These new developments allow for unlimited control over variables such as:

1. Level and duration of background and pulse current
2. The rate of drop and drop of pulse current
3. The frequency of pulse

Primarily, there are two types of pulse arc systems:

I. Pulsed arc with constant deposition efficiency

In DC mode, these use thyristor rectifiers in the 25–150 Hz range, or they may be computer controlled with a switching facility that gives different modulation types, and their combination is also possible. These also have control regulations and current rise and drop curve facilities.

The principle characteristics are that they are capable of controlling any of the following modes:

- One droplet per pulse
- Several droplets per pulse
- Droplet detachment after every second or third pulse
- Droplet transfer operations with bridging—achieved in short time arc interruption

In AC mode, the system works with an inverter, and the computer-controlled power uses a switching power section. The system's limitation is in relatively poor penetration due to increasingly negative background current, but it has high deposition rate.

II. Pulsed arc with periodically changing deposition efficiency

These are also computer-controlled power supply systems with switching sections. The main feature is the periodic power changes in the pulse arc mode of the working range.

In AC mode, the periodic power changes take place between short arc and pulse arc range.

In both AC and DC power supply systems, the following features are common.

The deposition rate, heat input, and penetration are based on the high power phase at the given welding speed.

In the lower power phase, the cooling of the weld starts, which can lead to weld pool collapse.

Programs are available that can provide smooth transition from these two points in welding.

The power sources are now capable of periodically changing pulsed arc power sources, where high and low energies are alternating, to achieve efficient metal transfer. These improve control over the weld pool in overhead, horizontal, and vertical up positions.

The process is capable of providing better controls on grove shape deviations and difficult welding positions with the variations of parameters.

Calculating heat input in pulsed arc GMAW

The concept of heat input and its role on the integrity of weldment is discussed in the physics of welding in Chapter 2. Heat input is an important aspect of all welding, where the control on the resulting microstructure of steel is important. The importance of heat input is especially of significance to steels sensitive to heat input; alloy steels that are required to have good toughness properties, especially with low temperature ductility; and quenched and tempered alloy steels where controlled heat input is desired where welding engineers specify the limits.

Heat input is related to welding voltage, welding current arc, and welding arc travel time, or dwell time of the welding arc, which is related to the travel speed in unit time when the arc is at a specific spot during welding. The calculated value is often reported in units of energy input.

$$\begin{aligned}\text{Heat input (in kJ/mm)} = &\{V \times I \times 60 \times \text{Process efficiency (Table 2-3-2)}\}\\ &\div \{\text{Travel speed (in mm per minute)} \times 1000\}\end{aligned}$$

This calculation is easy for processes that have constant-current output and arc voltage, where the data input for the calculation is a measurement taken from the meters. This is due to nonpulsed current and conditions, where simple arithmetic mean of power values can be the most effective way to calculate the heat input.

However due to the nonconstant, for example, the output in a pulsed arc process, this simplistic approach is not effective.

As we have seen in the previous description of pulsed arc welding systems, the current fluctuates between high peak amperage for the pulse mode and a low background current for regular cycles. This mode gives what is called an “apparent” square wave, because it is not exactly a squire wave due to the inductance and resistivity effect; the wave adopts a slightly roundish appearance. Several research works have been carried out and published (M.R. Bosworth; WRC Supplement to 111-s and AWS Welding Journal, May 1991) that suggest, that to obtain correct heat input, the power delivered to the arc should be measured as an arithmetic mean of instantaneous power values. The arc voltage is measured as close as possible to the arc between the work-piece and the welding gun.

The arithmetic mean is calculated using the following relationship between current and voltages of various passes.

$$P_{av} = \sum_{i=1}^{n} (V_j I_i) \div n$$

The root mean square (RMS) calculation of same data could be carried out using following relationship.

$$RMS = \left\{ \sum_{I=1}^{n} (X_i)^2 \div n \right\}^{0.5}$$

Where X_i is the first value, and X_n is the n values.

Power values can be further derived from using these obtained data and substituting them into the following relation.

$$P = V_{av}\, I_{av}$$

Where the P is the average power, and V_{av} is the arithmetic mean voltage.

$$RMS = V_{RMS}\, I_{RMS}$$

Where P_{RMS} is the root mean square power, and I_{RMS} is the root mean square current.

Thus, in the determination of more accurate thermal efficiency of a pulsed GMAW process, the RMS values are more effective over the arithmetic mean values.

There are, however, several variable considerations that make this approach more effective in calculation of realistic values. These variables could be the weld design, the shielding gases, and position of welding.

III. Spray Arc

The spray arc system is the traditional spray arc mode. The process is a high deposition process; hence it is always preferred for fill-and-cap passes. The droplet transfer method has high current density at the droplet neck caused by the short circuit bridges. The necking of the droplets occurs due to the pinch effect. This has the effect of reducing the rise of short circuit duration and welding current.

In new spray arc welding processes that have computerized control over the power, the arc voltage of can be further lowered, maintaining control over spatters. This allows for production of a directionally stable short arc. This has significantly high plasma pressure on the weld pool. The spray arc literally burns into the molten pool, hence the spatter if any also melts into it. Digital regulators step in to smoothen the welding current when long-lasting short circuiting occurs.

Higher frequency pulsed current is also used in some new developments to superimpose on the actual welding current to further constrict the spray arc and reduce the size of droplets. A similar effect is also achieved by imposing DC with certain harmonic content.

An overview of the typical range of current and voltages in which different GMAW processes operate is depicted in Figure-2-3-4.

Flux cored arc welding (FCAW)

Process fundamentals

In the flux core arc welding (FCAW) process, the arc is maintained between a continuously fed filler metal electrode and the weld pool. Shielding is obtained from a flux contained within the tubular electrode, in which case it is called self-shielding FCAW. The alternative is to supply an external shielding gas, in which case the process is called shielded FCAW (FCAW-S).

The flux-cored electrode is a composite tubular filler metal electrode with a metal sheath and a core of various powdered materials. An extensive slag cover is produced during welding. Self-shielded FCAW protects the molten metal through the decomposition and vaporization of the flux core by the heat of the arc. Gas-shielded FCAW uses a protective gas flow in addition to the flux core action.

Figure 2-3-4 (A) Mechanized welding being performed; (B) mechanized welding of 48-in. diameter pipe.

The FCAW process combines the productivity of continuous feed wire welding and the metallurgical benefits derived from the use of flux and the support of slag in shaping and protecting the weld bead from contamination and providing controlled cooling of weld metal.

Principal applications of FCAW

The self-shielded method can be used for nearly all applications that would normally be done with the SMAW process, and the gas-shielded (FCAW-S) process would cover most of the applications that would be done with a GMAW process.

The process has higher productivity comparable to the SMAW process; this can be the chief benefit of FCAW for most of the applications. Equipment costs are higher, setup and the operation is more complex, and there is a limit on the operating distance from the electrode wire feeder. The application of this process may be limited by the availability of suitable filler wire and flux combinations for various metals and alloys.

FCAW process generates large volumes of fumes that must be removed for the safety of people in the vicinity of the work; similarly, the slag must be removed between passes to keep the weld free from slag inclusions.

Shielding gases

Carbon dioxide is the most widely used shielding gas for FCAW as it is cheap and helps in deep penetration. The CO_2 atmosphere can act as either a carburizing or decarburizing medium, depending on the material being welded. If decarburization occurs (in metals with more than 0.10% carbon), carbon monoxide can be trapped in the weld metal and cause porosity in the weld.

Gas mixtures are also used to take advantage of the different gas characteristics. Like the GMAW process, the most commonly used gas mixture used for welding carbon steel is a 75% argon and 25% CO_2 commercial mix.

Electrodes

Because a wide variety of ingredients can be enclosed in the tubular electrode, FCAW has good versatility for alloy steels. Alloying ingredients are often included in the core of the wire. AWS Specification A5.20 includes the mild steel electrodes. E70T-1 is an electrode with 70 ksi tensile strength, tubular construction, suitable for flat and horizontal position welding, with a specific chemical composition. AWS Specification A5.29 includes the low-alloy steel electrodes. FCAW electrodes are also specified for surfacing, for stainless steel (AWS A5.22), and for nickel alloys (AWS A5.34).

Submerged arc welding (SAW)

Process description

The submerged arc welding (SAW) process uses arc to heat and melt the metal being welded. Because the arc is buried under the mound of flux, the arc is invisible to the naked eye. This characteristic gives the process the name "submerged" arc welding.

The arc is struck between the work and the electrode from the nozzle, and this arc provides the required heat for welding. The arc and molten metal are buried under a blanket of granular fusible flux continuously dropping through a chute on the work. The filler metal is obtained from the electrode, and sometimes the additional alloying elements are also supplemented through the welding fluxes.

The flux's main role is to stabilize the arc, determine the mechanical and chemical properties in the weld deposit, and maintain quality of the weld.

SAW is a versatile commercial production welding process capable of making welds with currents up to 2000 A using single or multiple wires or strips of filler metal.

The business end of a continuous bare wire electrode is inserted into a mound of flux that covers the area or joint grove to be welded. After the arc is initiated, a wire feeding mechanism begins to feed the electrode wire toward the joint at a controlled rate. The feeder is moved manually or, more commonly, automatically along the weld seam. Sometimes the welding head is kept stationary, and the work is moved under the welding head; most pipe mills use this practice.

Heat evolved by the electric arc progressively melts some of the flux, the end of the wire, and the adjacent edges of the base metal. A pool of molten metal is created beneath the layers of the liquid slag. This pool is in a very agitated state, and gas bubbles are swept up to the surface. The flux floats on the molten metal and completely shields the welding zone from the atmosphere.

Materials

Carbon steels up to 0.29% carbon, low-alloy steels up to 100 ksi yield strength, chromium-molybdenum alloys up to 9% chromium and 1% molybdenum, stainless steels, and nickel alloys are often welded with the SAW process.

SAW electrodes can produce matching weld deposits by varying the electrode-flux combinations. SAW electrodes vary in size from 1.5 to 6 mm (1/16–¼ in.) in diameter and are usually packaged in drums or coils of up to 1000 pounds (454 kg) in weight.

Fluxes are granular mineral compounds mixed according to various proprietary formulations.

Fluxes may be fused or bonded, and sometimes more than one type is mixed for highly critical or proprietary applications.

AWS specifications use a classification system to describe flux-electrode combinations, for example, F7A6-EM12K is a designation for a flux and electrode combination that will produce weld metal with 70 ksi tensile strength in the as-welded condition, with Charpy V-notch impact roughness of 20 ft lb at −60°F when produced with an EM12K electrode.

Other common joining and welding processes

Electroslag welding (ESW)

Electroslag welding (ESW) involves a molten slag that melts the filler metal and the surfaces of the work-pieces to be joined. The volume of slag moves along the full cross-section of the joint as welding progresses, and the slag shields the weld pool. The process starts as the arc is initiated. The arc heats the granulated flux and melts it to form the slag. As sufficient volume of slag is created, the conductive slag extinguishes the arc. The existing slag is kept molten by the resistance of the slag as the electric current passes between the electrode and the work-pieces.

The ESW process has extremely high rate of deposition, and it welds very thick sections of material in a single pass. The process requires minimum joint preparation thus reducing the cost of material handling, which could add significantly to the overall cost of welding and fabrication. Due to very high deposition rate and single-pass welding, the material distortion is minimal.

The ESW process can only be used on carbon steel and low-alloy steels, and must be performed in the vertical position. Welding must be completed in one cycle and cannot be interrupted. Material to be welded must be at least 19 mm (¾ in.) thick, and welding must be performed in the vertical position.

Plasma arc welding

In the plasma arc welding (PAW) process, the heat is produced between an electrode and the work-piece by heating both with a constricted arc. Shielding is obtained from a hot ionized gas delivered through the torch. A supplementary shielding gas is usually provided. From the process point of view, it is the constricted gas flow that differentiates the PAW process from the GTAW process.

The plasma issues from the nozzle at about 16,650°C (30,000°F), which allows for better directional control of the arc. High heat results in deep penetration and a very small heat-affected zone. The major disadvantage of PAW is high equipment expense.

As stated in the introduction of this process, PAW process is about striking an arc and forcing the hot ionized gas through the nozzle. The PAW process is an extension of the GTAW process. However, it has much higher energy density and greater velocity of the plasma gas through a constricting nozzle.

The process involves directing the orifice gas through the constricting nozzle's plenum chamber. The tungsten electrode in the center and the walls of the constricting nozzle form the plenum chamber. The chamber's exit end is constructed to give a tangential vector that forms a swirl to the exiting plasma gas. The throat length and the orifice diameter define the constricting nozzle. The tungsten electrode located in the center of the constricting nozzle is offset (set at a distance) from the opening of the constricting nozzle. This distance is called the electrode setback distance. This is a significant departure from the GTAW process where the electrode is extended out of the nozzle to strike the arc on the work-piece.

The offset of the tungsten electrode allows for the collimation of the arc focused onto the relatively very small area of the work-piece, as the shape of the arc is cylindrical as contrasted with focused beam. There is no change in the area of contact as the standoff varies during the welding process. Furthermore, as the orifice gas passes through the plenum chamber, it is heated and expanded, increasing in the volume and pressure; this increases the velocity of the gas that exits from the orifice. This is a very important variable in welding, as too powerful gas jet can cause turbulence in the weld pool. Hence the gas flow rate at the orifice is controlled within 0.25–5 L/min (0.5–10 ft^3/h). The additional shielding gas is introduced to protect the weld pool from atmospheric contamination. The gas flow rate of shielding gas is kept in the range of 10–30 L/min (20–60 ft^3/h).

The effect of a plasma jet created by constricted flow has the following benefits.

1. Improvement in directional stability of the plasma jet due to its ability to overcome effects of magnetic fields
2. Higher current density and temperature can be produced by the plasma arc

It may be noted here that the heat produced by a nonconstricted arc like that in the GTAW process is high enough to melt most of the metals that are welded. Hence the objective is not to generate too high heat, but rather the objective is to get more directional stability and focusing ability of the plasma jet and thereby of the plasma arc. This is an efficient use of the energy supplied by the process.

The degree of arc collimation, arc force, and energy density available on the work-piece are functions of several parameters. These parameters can be altered to a degree to produce very high to very low thermal energies as required by the work-piece.

- Plasma current
- Orifice diameter
- Type of orifice gas
- Flow rate of orifice gas
- Type of shielding gas

Two different arc modes, transferred arc and nontransferred arc, are used in the PAW process.

In the transferred arc, the arc is transferred from the electrode to the work-piece because the work-piece is made part of the electrical circuit. Mostly positive polarity is used for welding of all steel and nickel alloys; light alloys like aluminum and magnesium are welded with DC or AC with continuous frequency stabilization. In the transferred arc system, the heat is obtained by both the anode spot on the work-piece as well as from the plasma jet. Obviously, this system has an advantage of greater energy over the nontransferred arc system, hence its use for welding.

By contrast, in the nontransferred arc system, the work-piece is not part of the circuit; rather the arc is established and maintained between the electrode and the orifice of the constricting nozzle. The application is via the plasma jet, which is the sole supplier of the required heat in this system. This process with relatively low energy is especially useful for cutting and joining nonconductive materials.

The main advantages and limitations of this process are listed in Table 2-3-4.

Stud welding

Stud welding is a general term used to describe joining a metal stud or similar part to a metal work-piece. Welding can be done with many processes such as arc, resistance, friction, and percussion.

Arc stud welding joins the base (end) of the stud to the work-piece by heating the stud and the work with an arc drawn between the two. When the surfaces to be joined are properly heated, they are brought together under low pressure, resulting in the joining of the two at the interface.

Table 2-3-4 Advantages and limitations of plasma arc welding processes.

	Advantages of PAW process	**Limitations of PAW**
1	Energy concentration is greater, resulting in: • Higher welding speed • Lower current required to produce given weld • Lower shrinkages and distortion Adjusting welding variables can control the depth of penetration. Keyhole technique allows for higher thicknesses being welded with minimum distortions, minimum addition of weld metal, and the wine glass appearance of weld cross-section.	Very low tolerance for joint misalignment
2	Arc stability is improved.	Manual PAW is not very feasible to use, hence automation is the most practical application.
3	Arc column has greater directional stability.	The constricting nozzle requires regular inspection and maintenance.
4	Higher depth-to-width ratio results in less distortion.	
5	Fixturing cost can be reduced.	
6	This operation is much easier for adding filler metal to the weld pool as torch standoff distance is generous, and the electrode cannot touch the filler or the weld pool. This also eliminates tungsten contamination of the weld.	
7	Reasonable variations in torch standoff distance have little effect on bead width or heat concentration at the work, which allows for out-of-position welding.	

Capacitor discharge stud welding is performed with heat derived from the rapid discharge of electrical energy stored in a bank of capacitors. The rest of the process is similar to arc stud welding. As is described before, the different types of stud welding processes are similar in all respects except in the application of heat to the metal surfaces to be welded together.

Oxyfuel gas welding

In the oxyfuel welding (OFW) process, the base metal and filler metal are melted using a flame produced at the tip of a welding torch. In this process, a fuel gas and oxygen are combined in a mixing chamber and ignited at the nozzle tip.

The process derives heat for welding by burning two gases; sometimes, the process uses part of the required oxygen gas from the supply and supplements the rest from the atmosphere, as is the case with an oxy-acetylene process.

An advantage of OFW is the independent control that the welder has over the heat and the filler metal. This gives the process a clear advantage for use for repair welding and welding thin sheet and tubing.

The equipment for most of the oxyfuel process is low cost, portable, and versatile.

The process is also used as a cutting tool. Cutting attachments, multiflame heating nozzles, and other accessories are available. Mechanized cutting operations are easily set up and widely used in a variety of ways.

For cutting, the flame is used to heat a spot on the metal to be cut. When the temperature is reached, extra flow of oxygen is introduced to burn off the metal, and continued heating and flow of oxygen effects cutting.

Brazing and soldering

Brazing is the process in which the base metal is not melted. The process joins materials by heating them in the presence of filler metal that melts and spreads in the abutting surfaces of the metals by wetting and capillary reactions. The liquidus temperature of the filler metal is above 450°C (840°F) but below the solidus of the base metal.

Soldering follows the same principals as brazing except that the filler metal liquidus is below 450°C (840°F). The base metal liquidus is much higher than the filler metal. The filler metal distributes itself between the closely fitted surfaces of the joint by capillary action.

Parts must be properly cleaned and protected by either flux or a controlled atmosphere during the heating process to prevent excessive oxidation. A capillary opportunity to the filler must be provided, and the heating process must provide the proper brazing temperature and uniform heat distribution.

Heat sources include furnaces, induction heating coils, resistance heating, dip brazing in molten metal or molten chemical baths, and infrared brazing.

AWS Specification A5.8 divides filler metals into seven different categories and various classifications within the categories. Aluminum-silicon, copper, copper-zinc, copper-phosphorous, silver, gold, nickel, and cobalt fillers are commonly available.

Joint clearance has a major effect on the mechanical performance of a brazed joint. Clearance controls the mechanical effect of restraint to plastic flow of the filler metal; restriction to the good flow of the joining metal could lead to defects such as slag entrapment, voids, and capillary force. This also affects the amount of filler that must be diffused with the base metal.

Fluxes are often required to react with the oxidized surfaces of the base metal to clean the surface and allow and maximize the filler metal flow. Fluxing also roughens the surface to enhance wetting and capillary flow of filler metal.

Hyperbaric welding

Hyperbaric welding is the process of welding at elevated pressures, normally underwater, but it could be dry and the outside water is in a pressure chamber. To distinguish the two conditions, the term *hyperbaric welding* is often associated with welding outside water in dry conditions and the term *underwater welding* is specifically used to indicate exactly what the term says, which is welding underwater.

The applications of hyperbaric welding processes are diverse; in its wet form (underwater), it is often used to repair ships, offshore oil platforms, and offshore pipelines. Steel is the most common material welded. In the dry form, it is used to weld some very exotic weldments involving environmentally sensitive material often associated with aeronautical and aerospace components. The pressure chamber for dry hyperbaric welding is filled with inert (or nonreactive) gas mixture in a sealed container to control the environment. The controlled environment leads to improved process performance and weld quality.

Dry hyperbaric welding conditions are also coupled with underwater welding to improve the quality of welds. This type of weld has been attempted to the depth of up to 1000 m (3300 ft).

The weld quality of underwater welds is difficult to maintain, and the use of NDE methods and postweld examinations show they produce limited results.

GTAW is most commonly used, however other welding processes such as SMAW, FCAW, GTAW, GMAW, and PAW could operate at hyperbaric pressures. However, the parameter controls and weld quality are affected as the pressure increases, because the pressure affects arc behavior linked to the gas flow regime around the arc. The arc voltage is increased due to the pressure.

Special control techniques are developed that could allow welding to a depth of up to 100,000 ft (2500 m). However, dry hyperbaric welding is mostly limited to a depth of less than about 16,000 ft (400 m), due to welding divers' physiological limits.

Wet underwater welding commonly uses a variation of SMAW, employing a waterproof electrode. Other processes used include flux-cored arc welding and friction welding. In each of these cases, the welding power supply is connected to the welding equipment through cables and hoses. The process is generally limited to low carbon steels because of risk of hydrogen-induced cracking.

By the very nature of the electricity of welding power and water associated with underwater welding, there is risk of electric field leakage. This can be dangerous and life-threatening to the welder and other divers in the water. Safety measures may include that the welding equipment is suitably insulated and adaptable to a marine regulations.

Arc-welding power sources

As we have seen in the discussion of the welding processes, there are various arc-welding processes, and many of them also have a number of subvariants; all these processes use specialized power sources that address specific characteristics of the electric arc to give a special edge to the process. We shall discuss some of the more common power sources in subsequent paragraphs.

The available line voltage in the industrial world is generally very high. Because we know welding requires low voltage, they are not fit for welding use in a supplied condition. The welding power source must be able to reduce this high input voltage of 120 V, 240 V, or 480 V to suitable output voltage, usually in a range from 20 to 80 V. An intermediary component that steps down the line voltage is a transformer, solid-state inverters, or motor generators. They are all capable of converting the line voltage to required input voltage suitable for welding.

Some welding sources are linked with their own prime mover linked to a generator or alternator that produces the required open circuit voltage (OCV) for arc welding.

As these intermediary components convert high voltage to low voltage, they also provide high welding current in a general range of 25–1500 A (A). The output of a power source can be AC or DC, and some sources are capable of producing both AC and DC, so the required current can be obtained by changing the switch. The output may be either constant-current, constant-voltage, or both. Some power sources have a mode that is able to provide pulsating output. Transformers can deliver only AC, but a transformer coupled with a rectifier system can deliver both AC and DC. Because of these types of cross-variations, the sources are often described in very different ways, for example, a power source for a GTAW process may be called a "Constant-current AC/DC Transformer rectifier." These sources are further described by their current rating, input power requirements, duty cycle, etc. Further classification will include such special features as current pulsing ability, line voltage compensation, remote controlled, water- or air-cooled, high frequency stabilization, etc.

The classification, constant-current or constant-voltage sources, are based on static volt-ampere characteristics. These conventional power source terms are very relative, as in fact there is hardly any output of constant-voltage or constant-amperes. However new equipment is available capable of holding the current or voltage truly constant. The constant-voltage sources are also referred to as constant potential power sources; similarly, constant-current sources are also called variable-voltage units.

Constant-voltage power source

Constant-voltage power sources are used in welding processes that are self-regulating and use constant feed electrodes, mostly in the form of wire. The system stabilizes the arc with constant changes of the torch position. The arc current is kept in a nearly fixed proportion to the wire feed rate. National Electrical Manufacturers Association (NEMA) in its publication *Electric Arc Welding Power Sources* defines a constant-voltage source as "A constant-voltage arc welding power source is a power source that has means for adjusting the load voltage and which has a static volt-ampere curve that tends to produce a relatively constant load voltage. The load current, at a given voltage is progressive to the rate the rate at which a consumable electrode is fed into the arc."

Figure 2-3-5 shows a typical volt-ampere output relationship for constant-voltage power source; due to the internal electrical impedance there is a minor drop in the slope. It may be noted that, from point Y on the slope that corresponds to at 200 A

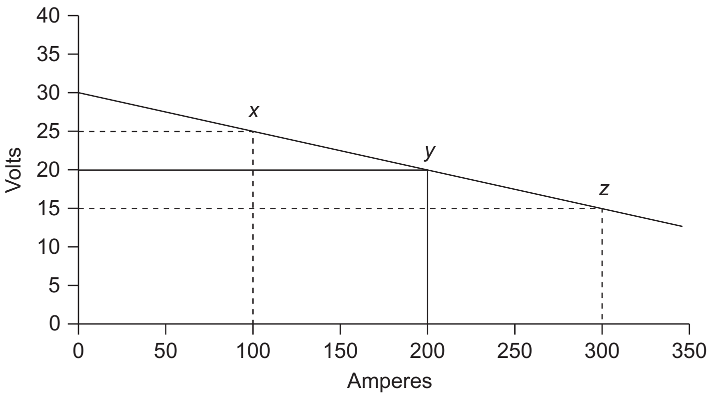


Figure 2-3-5 Volt-ampere output relationship for constant-voltage power source.

on X-axis, any variation in voltage (on Y-axis) toward points X or Z on the slope has corresponding changes in amperes. The volt-ampere characteristics shown by this curve are suitable for any of the constant electrode feed welding processes, including GMAW, SAW, and FCAW processes. It is very well known about these welding processes that a slight change in arc length (voltage) makes a large change in the welding current.

The slope also explains the difference between static and dynamic power supply characteristics. In short circuit GMAW process, for example, when the electrode tip touches the weld pool, the electrical circuit is shorted, and arc voltage approaches zero. At this point, it is the inductance that limits the rapid increase in welding current. The dynamic characteristics designed in the power source compensates for the action by rate of current change, preventing any explosive dispelling of the molten weld metal.

Constant-current power source

Due to the variation in arc length, the manual welding processes use this type of power source. Both SMAW and GTAW process use this type of power source. However, with voltage-sensing devices, the power source can monitor and correct the arc length. With the voltage-sensing device, these power sources can be used for semiautomatic and automatic welding process like GMAW, FCAW, and GTAW.

NEMA defines a constant-current arc welding machine as a machine that "has means to adjust the load current and which has a static volt-ampere curve that tends to produce a relatively constant load current. The load voltage, at a given load current, is responsive to the rate at which a consumable electrode is fed into the arc, except that, when a non-consumable electrode is used, the load voltage is responsive to the electrode-to-work distance."

In such a system, each current setting results in a separate volt-ampere curve if rested under study conditions, as with a resistive load. The OCV of this type of source is significantly higher than the arc voltage. Figure 2-3-6 describes typical drooping arc

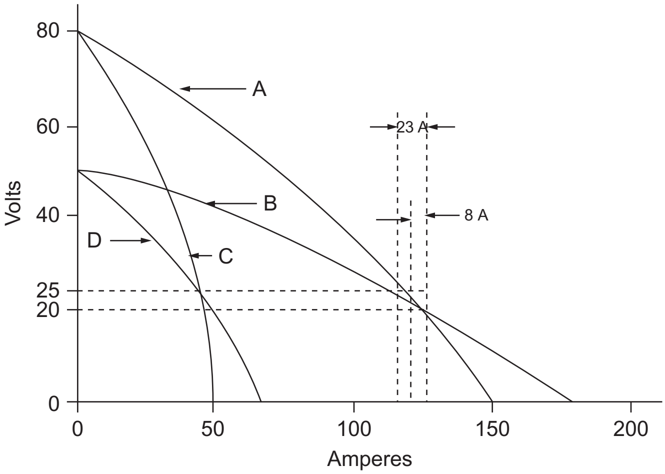


Figure 2-3-6 Volt-ampere characteristics of a drooping slope power source with adjustable OCV.

characteristics of a power source that had adjustable OCV. Such a power source may have both OCV adjustment and output current control. A change in any of the controls will change the slope of the volt-ampere curve. In Figure 2-3-6, curve A represents an OCV of 80 V; in this curve, a steady increase of arc voltage by 25% from 20 to 25 V would result in a decrease of relatively small current, by 6.5%, from 123 to 115 A. In this condition, in consumable electrode welding processes like SMAW, the electrode-melting rate would remain fairly constant with very slight changes in arc length. However, if the OCV of the power source was set lower, for example, at 50 V, then the same 25% change in arc voltage from 20 to 25 V would be responsible for a significantly higher change, about 19%, in current from 123 to 100 A. For the manual welding processes, an experienced welder would prefer a flatter Volt/Ampere curve power source, because this would give him the advantage of varying the arc length for an out-of-position weld, as in the pipeline welding.

Transformers

Welding transformers are simple transformers that have primary and secondary winding coils. The secondary coil has taps to vary the length of the coil and to draw selected current output. This also controls the OCV. The transformers work on the principle of maintaining the fixed ratio of input and output; it has fixed relations with input and output voltage, and an inverse relation with input and output current, as given in the following equation.

$$N_1/N_2 = E_1/E_2 = I_2/I_1 \qquad [3]$$

Transformers are designed by inserting an impedance circuit in series with secondary winding to provide an output volt-ampere slope characteristic that would adjust for welding condition upon selection of a specific tap.

In constant-current power units, the voltage drop across the impedance (E_x) increases as the load current is increased. This change in voltage drop causes a significant reduction in arc voltage (E_A). Adjustment to value of series impedance controls its voltage drop and the relation of load current to load voltage; this is called "slope control" or sometimes "current control."

In a constant-voltage source of power, the output voltage is very close to the requirement of the arc. In this case, E_x across the impedance reactor increases only slightly as the load current increases, with the reduction in load voltage being small. The control over the relation of load current to load voltage is achieved by adjustment of value of reactance, although it may be noted that this control is only very small.

Thyristor-silicon controlled rectifiers (SCR)

The term *solid-state device* derives itself from the science of crystalline solids. Unlike rectifiers that convert AC to DC, silicon diodes work as one-way valves when placed in the circuit. In proper arrangement, it is possible to convert AC to DC.

The solid-state devices have replaced the shunts, reactors, moving coils, etc. that were used to control the output of a welding transformer, as these solid-state devices are used to directly control welding power by altering the current or voltage wave form. Thyristor, a silicon-controlled rectifier (SCR), is one such device used for this purpose.

The two main function of a SCR is in phase-control mode with transformers and in converter configuration.

The common SCR phase-controlled machines are three-phase machines in either constant-current or constant-voltage modes. Because of electronic control of output characteristics, automatic line voltage compensation is easily achieved; this allows the machine to be set at the precise welding power, independent from the variations of input power. An SCR can also serve as a secondary contactor that allows the welding current to flow only when the control allows the SCRs to conduct. This is a very useful feature in spot-welding and tack-welding operations where rapid cycle operation is required. An SCR contactor does not provide electrical isolation; this requires that a circuit breaker or similar device be provided for electrical safety.

A transistor is another solid-state device, but unlike SCR they are expensive and provide a very precise number of variables to the power supply, thus limiting their use in common application machines. The conduction through the device is proportional to the applied control signal. If a small signal is applied, there is a corresponding small increase in conduction. And if there is no signal there will be no conduction. Unlike SCR, the control can turn off the device without waiting for polarity reversal or "off" time. The negative side is that transistors do not carry current like SCRs, as this requires several transistors to match the output of a SCR.

Transistors are used in power sources for modulation of frequencies, pulse width modulation, etc.

Development of square wave AC power sources

The use of AC current, with the help of SCRs and other current cycle rectification tools, has become possible and, in fact, led to more modern development of welding processes as described in the "newer variants" of GTAW, GMAW, and PAW processes in particular. Traditional use of AC power sources were limited to specific applications, as current range and remote control were difficult to achieve. This shortcoming was tied to development of amplifiers and silicon diodes. But the sector of industry that demanded higher quality and reliability of welds was still unsatisfied with this improvement of the processes.

This shortcoming of AC power sources for welding was overcome by modifying the current cycle of current flow. In a 60-Hz alternating current, the current is reversed 120 times per second. While the intermediary methods of magnetic amplifiers were used, the reversal occurred slowly and resignation of the arc from zero to full ionizing voltage was a problem. This low instant current was not able to improve the quality and reliability of GTAW, PAW, and GMAW welding processes, as the use of high frequency (hf) resignation systems were, in particular, causing more quality issues in these processes.

The development of square wave AC current allowed the trailing edge of the wave to remain ionized and the electrode tip hot enough to reignite the arc at opposite polarity and provide a continuation of the welding process.

These developments have allowed machines to achieve variations of current outputs, the positive side of the polarity. These features have allowed manufacturers to develop processes as discussed in the "newer variant" sections of welding processes discussed earlier.

Generators

In arc welding, rotating equipment is often used as power source. These are generators produce DC, and alternators produce AC.

Main or shunt field windings are used to control no-load output of a generator. A filter reactor or an inductor is replaced with several turns of a series winding on field poles of the rotating generator to provide inductance for stable arc. These machines allow changing the polarity by interconnection between the exterior and main field.

Alternator

An alternator is a rotating type of power source that produces AC that may be used as AC or rectified through a rectifying circuit to be used as DC for welding. For rectifying, it may use any of the methods discussed in this chapter.

Welding automation

4

Mechanized and automatic welding

In Chapter 3 of this section, we have referred to “automatic welding.” The need for automatic welding arises from a desire for higher production and elimination of human interaction in seemingly routine and repetitive work. It also promotes much higher performance level using higher currents and heat that is difficult, if not impossible, to use due to human tolerance and safety limits.

In fabrication and manufacturing industry, the term *automatic/automation* means that some of the functions or steps in an operation are performed by a mechanical or electronic device, or a combination of the two. Degree of automation is varied, as some functions may cover all operations or they may only cover some part of the operation.

The words *mechanized* and *automatic* are often used to describe such welding practices. The term mechanized is used to indicate that the movements of the welding process are simply mechanized and not many of the electronics are controlled by artificial intelligence (AI), although opinions exist with valid arguments that the use of the term *AI* may give an impression that the device is capable of self-learning, which it is not, but AI is a future possibility in the field. The current system is basically kinematic algorithms and calculations programmed into a system. By contrast, the word *automatic* is variously used; it implies that some degree of AI is used to manipulate the mechanical arms that could help the welding head (torch) to be moved along the weld line, or locate itself to difficult-to-reach welding positions as the welding progresses. In more complex forms, it may do all these while managing the current and weld travel speed, to a set range of parameter limits. It can also include much more complex controls that are taken away from operators’ controls and programed into the machine. It can include various parameter controls, and welding head and the job manipulation to conduct welding in the most effective way.

Welding automation is not just about the ability to put a welding head on a machine that is either an electronically articulated or mechanical arm, but it also involves a series of planning, organizing, and monitoring of the production process. It involves careful evaluation of the welding/production process, procedures, and production steps and controls, and then deciding which of those manually operated actions to use and to what extent they need to be automized. Because most welding activities are welder judgment dependent, it is important that an automation decision is based on identifying which activity can be freed from manual judgment and put on a machine; that machine may involve a complex electronic control system, it may use simple mechanical movements simulating manual welding, or it could be a combination of both.

The objective of automation is to reduce manufacturing costs by increasing productivity; it also aims at improving quality of production by moving repetitive movements

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from a manual to a mechanical means. The degree of sophistication is simply a matter of improvements on these basic goals.

Machine welding or mechanized welding is done by welding equipment under constant monitoring by a weld operator. The welding may be performed under a stationary head where the object is moved along the weld line for the weld head to weld, or it may be done where the object is stationary, and the weld head moves around the weld line to accomplish welding. In such a setup, the machine may or may not be able to load and unload the work to the weld station. A machine welding system may have one or a combination of the following:

- A machine carriage is the track to negotiate the weld line, which could be either a rail-mounted or tractor-type movement. Such a carriage could provide both horizontal and vertical movement to the welding head. Orbital movement is also used to weld girth welds in pipes or any round objects such as pressure vessels, tanks, etc. Because position and travel speed both are essential variables for welding, precise control of these movements is essential. In machine welding, this is carefully monitored by the welding operator.
- A welding head manipulator is essentially an extension of the welding head of the welding machine mounted on a boom. The manipulator has power to move the boom up or down the mast that is put on a swivel. A smooth movement of the manipulator is required for successful welding and quality production. Following are the basic elements of machine welding:
  - Travel speed
  - Continuous filler metal filling rate
  - Initiation and maintenance of welding arc
  - Movements of arc.

The operator's presence at the weld location is essential in machine welding, as the operator is required to observe the weld in progress. The operator interacts continuously with the weld equipment to assure correct placement of weld head and proper deposition of weld metal.

Automatic welding, in contrast to machine welding discussed before, is performed with equipment that performs the entire welding operation without any adjustments or monitoring by a welding operator. Although the operation of the equipment is independent of a welding operator, the operator is required to ensure that the electromechanical functioning of the system is in proper working order; thus the skill set of the operator is significantly improved in this respect. This requires proper training to understand the machine's functions and electronic system.

The system by itself may or may not be capable of loading and unloading the job to the weld station.

The elements of machine welding discussed earlier are used in automatic welding. The weld preparation is a very important factor in any quality weld; however, there is stringent demand for more precise weld preparation for successful welding by automatic welding. In the automatic welding process, the welding cycle controller is an important part. This controls welding operations as well as the material handling equipment and fixturing for the job. The controller accurately times these activities and various stages to allow for quality welding and fast production process. The effective result of automatic welding can result in:

- Consistent weld quality
- Increased productivity

- Predictable rate of production
- Reduced variable cost of welding
- The welding operation to be integrated with other production processes

As we can see, automatic welding is a very useful tool for fast and consistent production process where the work is relatively repetitive in nature. However, the system has some limitations that restricts its universal use. These limitations could include:

- Heavy capital investment
- Elaborate arc movement and control devices, which are preprogramed in the operation sequences
- Suitable only for large production orders
- Requires dedicated fixturing for accurate fitting and alignments of abutting warts to be welded

Successful application of automation of welding is possible by using robotic technologies; a *robot* is essentially a mechanical device that can be programmed to perform some programmed tasks, such as manipulation of weld head and positioning of work at the weld station.

These robots (read more about robots in the next paragraphs) can be used with the computerized numerical control technology to accommodate variations in job-work. This allows for the welding program (for example, welding parameters and job positioning) to be changed to accommodate for a different set of welding requirements. This combination of robots and computer numeric control (CNC) programing allows for relatively smaller work orders to be completed by an automated welding system, allowing for faster and quality turnaround on the shop floor. Robots and their computer memories are used to store a set of instructions for any future work of the same description. Robotic arms are often fitted with sensory eyes to determine if the weld joint fitting is within the required parameters, and this adds to the quality control efforts of the production process.

The basic understanding of what robots are and how they are articulated to perform various welding and manufacturing activities is important to understand the automation of welding function.

As we understand, various welding processes can be automized and they can be put on robotic heads, so it is important to learn about robots and the various types and articulation of robots. In the following paragraphs and figures, we discuss robots and show the motion of a robot in various axes. This ability defines the reach of the robot and the welding head to various angles and positions of welding locations on the job.

Welding automation and robots

As many welding process applications are repetitive, it is natural for engineers to look to automation. Across the welding industry, various nomenclature is used to describe a spectrum of automation implementation, ranging from an original manual welding process, to a mechanized carriage and track, to a fully automatic process. Generally, a distinction is made between the level of interaction by a welder/welding operator to the equipment configuration.

Manual	Mechanized	Robotic/fully automatic
Welder manipulates arc	Operator manipulates machine	Robot manipulates arc
Welder controls travel	Machine controls travel	Robot controls travel
Welder controls position	Operator controls position	Robot controls position

Degrees of freedom (DOF)

From a machine design and kinematic perspective, degrees of freedom (DOF) are often used to describe the number of axes in which a machine controls linear or rotational position, direction, velocity, and acceleration. A gantry-style machine could be constructed with three DOF in which any point (x, y, z) can be reached within its workspace. A common six-axis robot would have six DOF and the ability to achieve any inclination (roll, pitch, yaw) at any point (x, y, z) within its workspace.

Often systems for welding automation will have multiple DOF capability; however, they are not coordinated, or their axes are not controlled together. For instance, a simple carriage on a track can travel parallel to the track (first DOF, y-axis), steer/center torch perpendicular to the track (second DOF, x-axis), and adjust torch height (third DOF, z-axis). For many welding systems, these DOF are completely independent even if all the axes are mechanized. For example, the x-axis and y-axis could each be controlled by process-monitoring feedback or operator input. In some cases, these axes might be manually adjusted by the operator. Thus, the torch cannot perform repeated circular or diagonal paths in the xy plane or in xyz space. Plasma tables, CNC machines, and six-axis robots differ in this aspect of coordinated motion. This is often a distinction between mechanized and robotic/automatic; however, industries often interchange the two terms.

Workspace

Workspace is the point, line, plane, rotation, or volume of space in which mechanized machine or robot can reach with its tool center point (TCP). The workspace of common robots can be increased by adding additional axes to mobilize the robot rather than using a fixed robot.

Figure 2-4-1 depicts a spherical-type (its workspace would be spherical in shape) robot with five DOF:

one rotation at the base
one rotation at the “shoulder”
one linear actuation arm
two rotations at the “wrist”

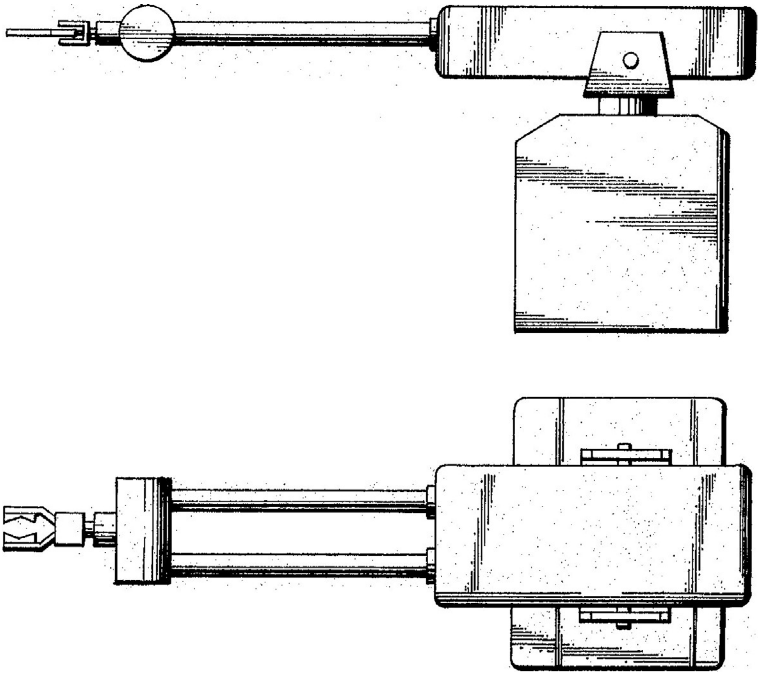

Figure 2-4-1 Spherical-type robot.

This robot type was one of the first industrial robots used in automotive manufacturing in the 1960s. These robots were fitted with resistance spot welding equipment as well as some GMAW/FCAW guns.

Figures 2-4-2 and 2-4-3 depict cartesian (its workspace would resemble a line or circle, similar to the track) mechanized “bug and band- type machines with one mechanized DOF:

one rail for the carriage to drive

These types of machines have many uses in the welding and cutting realms of manufacturing and construction. These systems are small enough to be portable and, with various tracks (linear, flexible, cylindrical, etc.), can be used for many different applications. The simplest models will only allow start/stop and speed settings, whereas other adjustments and process settings would have to be manually controlled. These simple models are common in shipbuilding and a wide range of linear structural component manufacturing. More sophisticated models might mechanize the height (up/down) control, steering (in/out), oscillation, welding start/stop, welding schedule by sector (orbital models), etc. The more sophisticated models are quite common in the pipeline construction industry. However, an operator is required to place the rail or band in position relative to the part and place the carriage (bug) on the rail (Figure 2-4-4).

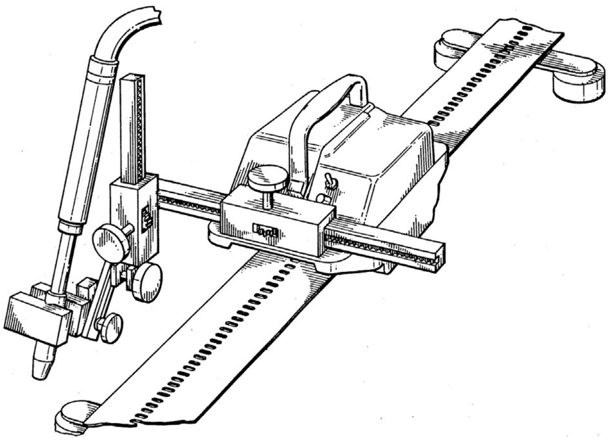

Figure 2-4-2 Linear bug and band-type machine.

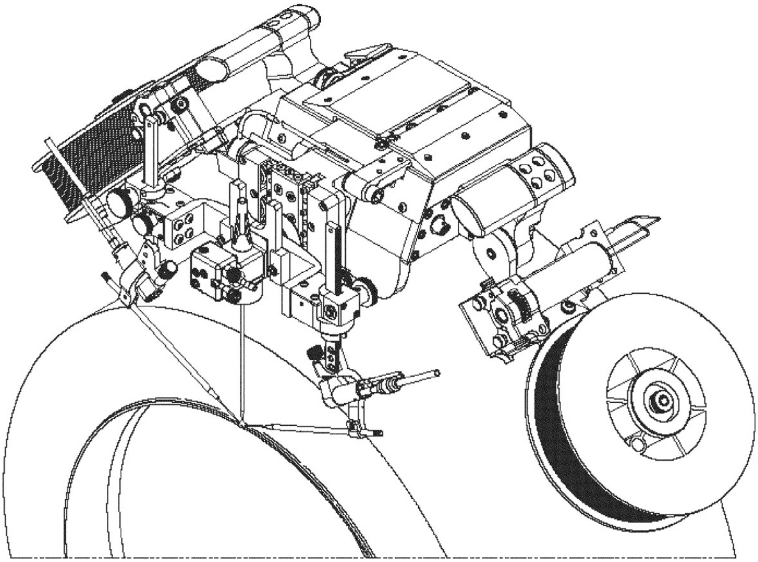

Figure 2-4-3 Orbital bug and band-type machine.

The previous robot illustration is a selective compliance articulated robot arm (SCARA) robot (cylindrical workspace) with three DOF:

one rotation at the base
one rotation at the "elbow"
one actuation of the end effector

These types of robots are less common for welding applications but may be used for assembly of parts to be welded or joined. They can be used in some resistance welding,

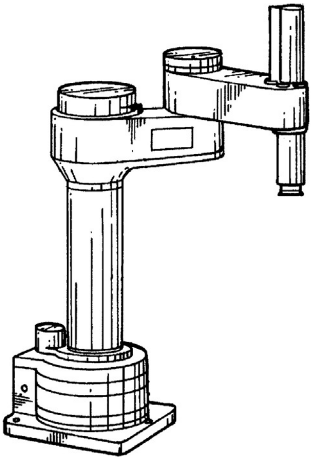

Figure 2-4-4 SCARA-type robot.

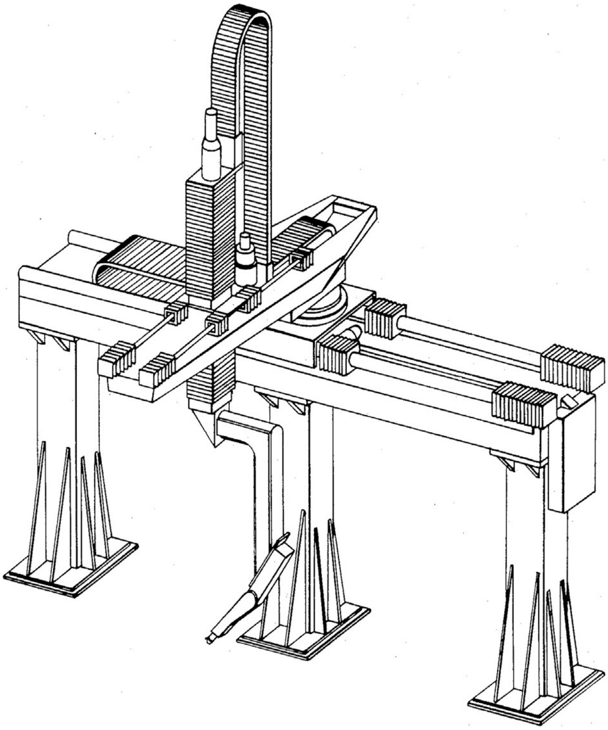

Figure 2-4-5 XYZ cartesian-type robot.

soldering, ultrasonic welding, or other specialized joining applications. Their advantage can be speed and rigidity in plane parallel with the articulation (Figures 2-4-5 and 2-4-6).

The previous mechanisms are cartesian-type automated systems that are often used for submerged arc welding (SAW) as well as other arc-welding processes.

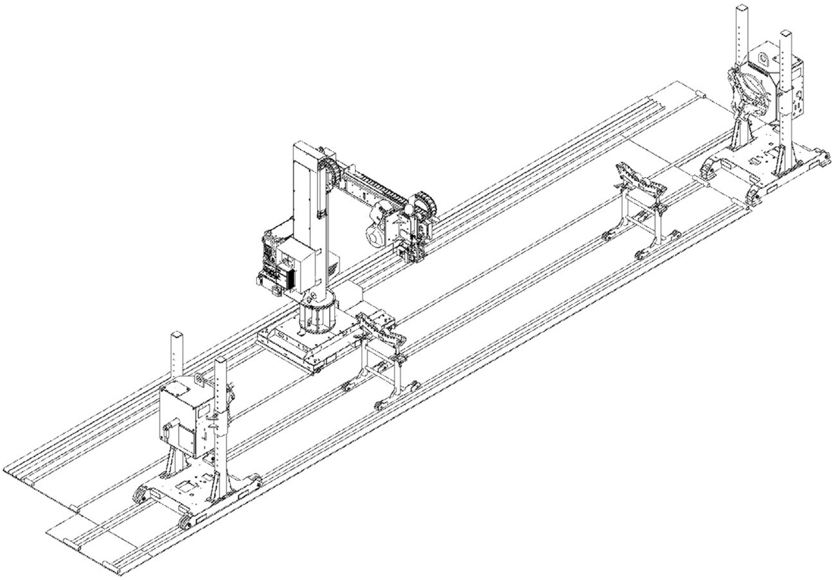

Figure 2-4-6 XYZ cartesian-type robot with headstock and tailstock.

These systems may have three or more DOF (rectangular prism workspace). Some applications may include auxiliary axes that rotate a pipe spool or fitting for welding.

The base three DOF include (illustrated in drawings):

one actuation for translation in the x-axis
one actuation for translation in the y-axis
one actuation for translation in the z-axis

The side beam configurations are popular for seam welding, girth welding, and cladding of tubular products. They can also be used for linear welds in thick sections. Most systems do not incorporate coordinated motion, and only one axis is used to drive welding speed. Cladding systems may be more sophisticated to provide additional dimension(s) to the process.

When it comes to the design of an automated system, generally there is a main axis in the direction of the main weldment to be created. Additionally, there is an axis transverse for steering (in-out) and an axis for height control (up-down). These axis lengths can easily be designed to accommodate the desired workspace for the welding application. It is also good practice to start with the longest axis as the base, add the next longest axis to it, then finish with the smallest axis. This minimizes the weight each axis must bear in the complete system, which usually optimizes costs (Figures 2-4-7 and 2-4-8).

The previous (newer) illustration shows examples of articulated six-axis industrial robots with six DOF.

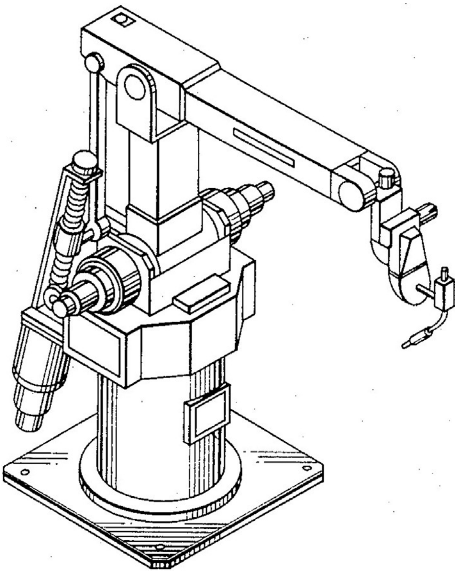

Figure 2-4-7 Five-axis articulated industrial robot (older design).

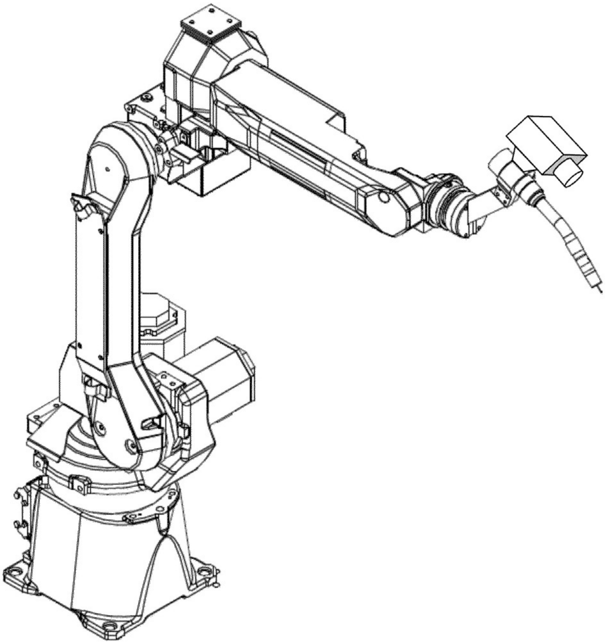

Figure 2-4-8 Six-axis articulated industrial robot (newer design).

Six-joint rotation axes

The six-axis robot is one of the most common welding robots. It accommodates arc welding well with the dexterity capability to orient the torch and achieve trajectories for welds in many different sizes, shapes, configurations, and orientations. Because of its popularity and abundance, it is often more economical to use a six-axis robot even when the application does not require six DOF. These types of robots are flexible and versatile. In fact, for many companies the same robots have worked through several different product line cycles, because they can be reconfigured to weld different parts with little hardware reconfiguration. These robots can also be integrated into larger manipulators for increased workspace, multiple cell-to-robot work, or multiple robot-to-cell work.

TCP is the center point of the effective end of the tool for robot or automated machine. For a simple GMAW robot, it is the center of the end of the wire after it has been trimmed to the appropriate stick-out length. This is the point at which the robot is controlling position, trajectory, velocity, inclination, adjustment, etc.

Position control

For six-axis robots, programming has been historically point-to-point. Generally, a part is mocked up, and each weld is programmed by teaching the robot each point step-by-step. Arc-welding robots are somewhat unique in that the path between points is a more important feature than for pick-and-place robots, such as large-part handling robots or spot-welding robots. Thus, for arc-welding robots, circular moves can be made as well as linear moves. This programming process can be tedious and expensive when large manufacturing lines must be paused for this exercise. However, offline programming has helped allow parts to be programmed virtually rather than physically, reducing the downtime of continuous manufacturing lines.

In terms of accuracy and precision, most robots are capable of repeating position within 0.1 mm. However, this often depends on the reach and payload capacity of the robot. For arc welding, a general industry practice is to maintain repeatable positioning within one-half of the diameter of the filler metal. For most cases, this is precise enough for the process it is manipulating.

Sensing and accuracy

The future use of artificial intelligence may improve the ability of robots to carry out various functions in very precise manner. However, the current use of kinematic algorithmics and calculation affects the sensitivity of the robot, which affects the accuracy of the robot.

It can be appreciated that variances in both fixtures and parts exist, especially against a virtual program model. If the robot repeats its programmed positions step-by-step within 0.1 mm, the weld joint locations will likely be misaligned with the robot's paths. Additional programming strategies, such as touch sensing, thorough arc seam tracking, vision sensing, and vision tracking, can aid in teaching common six-axis robots to account for variances in the physical world. These features can make articulated robots more practical for higher product variation and custom product manufacturing.

Touch sensing uses the welding electrode to complete an electrical circuit to pinpoint actual location of the part, joint, reference plane, etc. for offsetting the original program. The robot will complete a series of movements in paths where position variation is important to determine start/stop locations as well as part types (Figure 2-4-9).

In lieu of touch sensing, a system and methodology was developed to allow non-contact position sensing and tracking. In this system, a laser "stripe" is projected on the weld joint at a known angle in front of a camera. The camera can triangulate the depth of points across the detected "stripe." Software allows a user to select key points from a simplified polyline generated from the profile of the strip. From these points, tracking and position references can be established for offsetting the tool position. Generally, these sensors are positioned to determine profile and offsets ahead of the tool; thus, the robot can account for the adjustment in step with the detected change.

Arc voltage control (AVC) has been used in many different automation configurations to maintain the torch-to-work distance during welding. For simple applications, it works by adjusting the height (usually z-axis) based on voltage for constant-current (CC) processes. Typically, this will be limited to use in the same axis as the welding torch. Other through-arc methods exist for use with constant-voltage

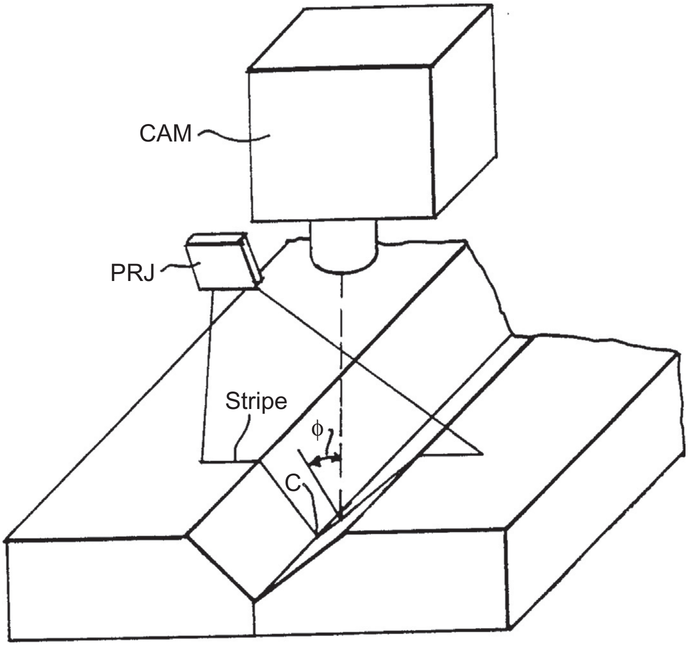

Figure 2-4-9 Laser vision camera system.

(CV) processes such as current, impedance, or combination measurements. For coordinated motion automation, like articulated robots, it is possible to know the axis of the weld torch in space and maintain torch-to-work distance in the actual orientation of the torch. Thus, simple cartesian-type systems or bug-and-band systems with automated height control will typically be used where height control axis can be maintained parallel with the welding torch (Figures 2-4-10 and 2-4-11).

Oscillation or weaving allows system configuration with a set size inverter and electrode to perform a wider range of weldments. Additionally, it is a technique that can help wet the weld pool to the sidewalls of a narrow groove weld joint. Oscillation can be a simple mechanical device added to the torch holder assembly or coordinated motion within the entire robot. Many articulated robots are capable of a variety of oscillation patterns (zig-zag, sinusoidal, figure eight, spiral, etc.). Through-arc seam tracking is another benefit of utilizing oscillation as the arc electrical characteristics sensed at various points throughout the oscillation cycle can be used to detect if the torch is centered in the joint. Based on this information, the robot can compensate to center the torch in the joint.

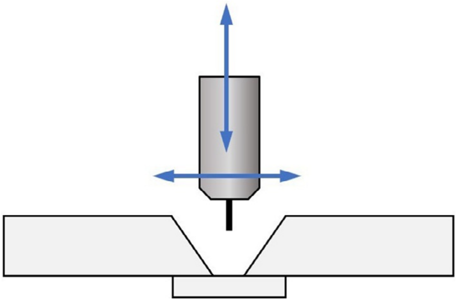

Figure 2-4-10 Simple cartesian motion height control and oscillation.

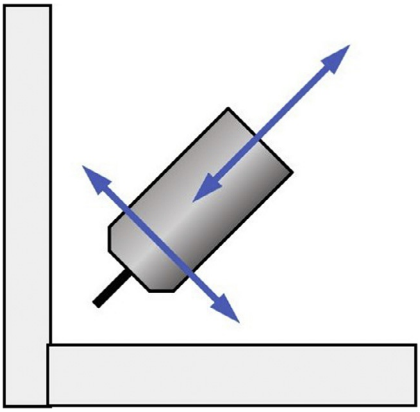

Figure 2-4-11 Coordinated motion height control and oscillation.

With the abilities of seam tracking based on vision or through-arc methods, adjustments of the welding parameters themselves can also be made. For instance, if the robot system detects that a weldment section is wider, the travel speed may be decreased and oscillation width increased to maintain the correct volume of filler metal deposit. In other cases, it may be necessary to adjust wire feed speed and corresponding arc parameters. Although the development and proving of adaptation settings may be complex for some applications, it may be beneficial and only possible with the help of robots paired with adaptive control capabilities.

Communication with welding power sources or inverters is becoming important as welding processes become more and more complex. Some power sources are capable of electrical characteristic changes at 500 kHz. For robot controllers to better make use of the power sources' capability, faster communication in the optimum configuration is necessary. This is another area in which popular preengineered articulated robot systems have the advantage over custom-developed cartesian style systems. These systems are more popular and, therefore, have undergone more integration with various power source manufacturers and generally keep closer pace with their communication improvements.

Designing for robotic automation and selecting automation for welding

Selection of welding automation for various applications can be straightforward or overwhelmingly complex. For simple or common applications, many preengineered and fully integrated systems exist. For others, a custom system must be developed, engineered, and integrated before implementation. When automation is considered for the first time for an application, it is important to understand the desired goals and weigh the feasibility of achieving these goals prior to investing in automation. This goal should highlight a step change that only the automation improvement can make possible. Some of the most common automation goals are centered on productivity, quality, safety, and ultimately economics.

Productivity by robotic automation of welding

It must be understood that, in most cases, welding speed is driven by the welding process rather than man or machine manipulating it. Some cases do exist where processes are made possible or practical with the help of automation (i.e., laser welding, orbital downhill GMAW, multiple torch welding, etc.). Automation can allow some improvement in allowing processes to be maintained in tighter optimum process windows, but most of the time this itself will not lead to significant productivity improvements.

Automation can significantly improve welding "on" time versus "off" time, and this often drives automation productivity improvement effects. This is usually accomplished by reducing the "off" time and increasing available "on" time. Although this may be largely reliant on the automation of the part handling and manipulation, a robot or automatic machine is generally able to reset and restart welding much quicker than a human. It may also have the dexterity and reach to complete longer welds in a single stroke rather than several by a manual welder. The extent of this improvement should be evaluated prior to large capital investments as, for most applications, this can be simulated and accurately calculated.

Quality of welding with the use of robots in welding

Quality is another key factor that may lead to more improvement than productivity but is often harder to realize. Automation can offer more repeatability and reliability that can significantly reduce rework or reject rates. However, it must be understood that welding automation cannot necessarily fix upstream quality issues. For example, if the variance of two mating parts is too great for proper fit-up, then the welding process may continue to struggle regardless of whether it is manual or automated. In some cases, a manual welder may be more capable to adjust to the variance to produce an acceptable weld. Alternatively, additional peripheral sensors may be required to allow an automated welding machine to account for the variance. If the variance of part dimensions, weld joints/areas, part positions/orientations, etc. are understood and accounted for in the engineering of the automation system, then most of the quality issues related to the automation system can be engineered out. Peripheral sensors may even be able to determine out-of-tolerance parts, assembly, etc. prior to welding, eliminating waste and rework.

Reliability aspects of automation can greatly improve quality. When certain procedures are necessary for quality results, automation can assure that these procedures are followed every time correctly. For instance, if a robotic GMAW welding application requires a weld assembly to be done in a certain order to control distortion, the robot will always carry out the programmed procedure in the order programmed. For some complex applications, manual welders cannot reliably perform these procedures without human error inevitably occurring.

Automation may not necessarily solve welding parameter or process implementation issues; however, the consistency of automation may make these issues easier to pinpoint and eliminate. Welding processes and procedures should be carefully evaluated and developed with automation equipment planned for production prior to implementation.

One distinct advantage to automated arc-welding systems is the control of travel speed. Travel speed combined with fixed or controlled welding parameters will maintain heat input characteristics reliably, which can be of utmost important for welding certain materials. Many manual welders can maintain certain ranges of travel speed/heat input when trained to a certain rhythm with the welding process; however, they are generally reacting to the weld pool and may speed up and slow down to achieve target averages rather than maintaining travel speed ranges as in automation.

Safety associated with use of robots in automation of welding

Safety can drive applications to use automation. In environments where a manual welder could be at risk, such as confined spaces, radiation-exposed areas, extreme underwater depths, around toxic materials, extreme temperatures, repair of pressurized vessels or pipelines, etc., automation may allow welding processes to be utilized without risking personnel. For less extreme applications, general automation does move the welding operator or robot operator further away from hazards such as hot work, fumes, ultraviolet radiation, heavy part manipulation, etc.

Many automated machines and robots can move faster than humans can react. It is standard practice for most robots to have governed speeds when being driven by a teach pendant or with operators present within the robot workspace envelope. Additionally, most robotic work areas are partitioned off with sensors indicating the all-access points are closed and personnel are clear before allowing the robot to continue in full speed automatic mode. Limit switches, dead man switches, emergency switches (e-stops), torque limits, collision sensors, etc. are commonly used to help mitigate robot and automated equipment risks to personnel. There are industrial standards available that outline good practice for safety facilities for various robotic and automated equipment.

Economics of using robots in welding automation

A medium-sized arc-welding robot with essential peripherals can usually be obtained for $70,000 to $120,000. For additional reach, payload, vision systems, or other peripherals, pricing can increase significantly. Fixtures and tooling can also be quite expensive as it is often custom engineered. Simple bug-and-band systems can range from $20,000 to $150,000. When purchasing a robot, it is necessary to understand what costs savings or return on investment is necessary to justify the purchase. Management must be supportive of automation throughout the production line and not just in the welding area as the upstream and downstream productivities should match the production goals of the welding robot and will ultimately contribute to a successful improvement with the welding automation implementation.

The following publications are recommended for further reading on the subject of automation and especially about robots and robotic welding automations.

Further reading

Niku, S.B., 2001. Introduction to Robotics: Analysis, Systems, Applications. Prentice Hall.

Robotic Industries Association (RIA), 1999. American National Standard for industrial robots and robot systems—Safety requirements. ANSI/RIA R15.06-2012, Robotic Industries Association, Ann Arbor, MI.

Welding Handbook, vol. 1—Welding Science and Technology (ninth ed.). American Welding Society (AWS), 2001.

Following are some of the US Patents associated with the subject:US3845284, US4590577, US4650959, US4833381, US5070792, US50687831, US20130119040A, UA20160082539A, US20170001268A.

Physical effect of heat on material during welding

5

In previous chapters, we discussed and understood that, in all welding process, we use heat to accomplish the joint. Except for a few exceptions, all welding processes use direct application of heat for welding, although the method to obtain that heat varies from process to process.

This application of heat is localized near the weld joint and affects the parent metal closer to the weld joint. This autogenous heating for welding is often by the current flow and contact resistance of the two metals being joined. In the history of development of welding, almost all-possible heat sources have been used. Some of the sources of heat in welding are an indirect by-product of primary process like friction, ultrasonic, or explosion methods used for welding.

Irrespective of how the heat is applied in a specific welding process, it is paramount that the process is in control of the conditions of heat. The thermal conditions are responsible for changes in metallurgical structure and mechanical properties, causing residual stress and distortions in the material. The four factors influenced by heat that affect the material properties are:

1. Distribution of maximum temperature, also called "peak temperature"
2. Distribution of heat between the weld-metal and heat-affected zone (HAZ)
3. Cooling rate in the weld-metal and HAZ
4. The solidification rate of the weld-metal

The physics of welding has been discussed as to how to model the effect of heat conditions in the weld. In this chapter, we shall discuss the practical applications of these effects of heat.

For this discussion, we will consider the effect of heat in a simple 0.20% carbon steel weld.

The molten metal

As soon as the flame or arc is directed to the steel, its temperature rises. The heat absorbed from the heat source spreads beyond the spot directly underneath. The temperature rises steadily at first. At about 510°C (950°F), any distorted grains resulting from previously working the steel starts to recrystallize.

The steel immediately surrounding the weld metal is in a mushy condition—there is a mixture of crystals and liquid. Inside the 850°C (1560°F) curve, the steel is in the gamma (γ) form, whereas between the temperature range of 510°C (1560°F) and 725° C (1335°F), the steel is a mixture of alpha (ferrite) and gamma (austenite) crystals.

Above 850°C (1560°F), the austenite crystals grow as many small austenite crystals coalesce to form fewer larger austenite crystals.

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At 1490°C (2714°F), melting begins and continues until 1520°C (2768°F) when the last of the crystals melt.

In the reverse cycle, as freezing begins at 1520°C (2768°F), crystals of austenite begin to appear, and as cooling continues, the proportion of austenite crystals increases and the melt becomes mushy.

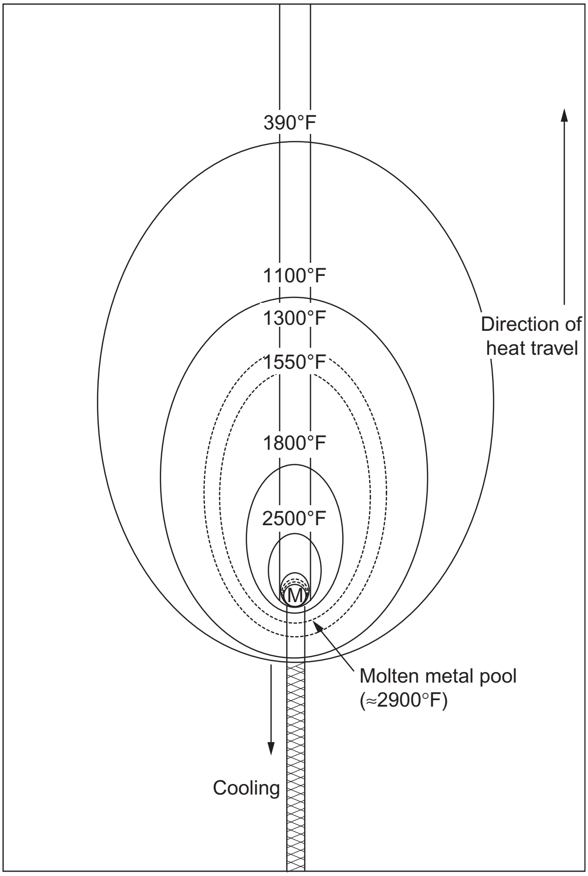
The tiny crystals start to replace the liquid randomly. The crystals grow in preferred directions until they come into contact with other growing crystals to form a polycrystalline metal. The initial crystals growing in the weld metal are columnar, and the later crystals are multiaxial. Between 1490°C (2714°F) and 850°C (1560°F), there is no change in the austenite crystals.

At 850°C (1560°F), ferrite crystals separate out from the austenite at the austenite grain boundaries. Just above 725°C (1335°F), 25% of the steel is ferrite and 75% is austenite.

Cooling continues until, at 725°C (1335°F), the austenite starts to transforms to pearlite.

The temperature distribution in a plate is graphically described in Figures 2-5-1 and 2-5-2.

Figure 2-5-1 Temperature distributions in a plate.



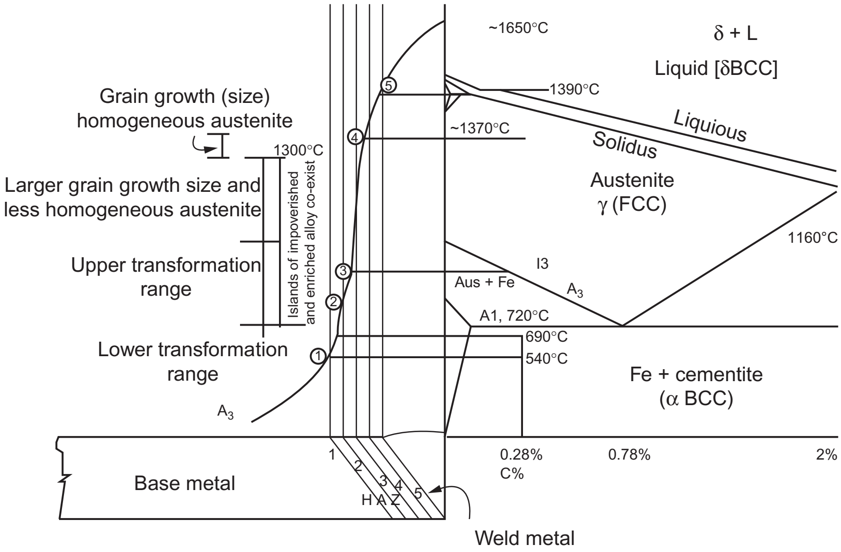


Figure 2-5-2 Temperature distributions in weldments superimposed on a phase diagram.

The welded plate

All parts of the plate that attained a temperature of about 1100°C (2000°F) will have the structures described earlier because the austenite transformations would have occurred.

The portion of the plate that was heated to above 850°C (1560°F) and up to 1100°C (2000°F) would have a more ductile structure. The faster cooling rates in this heat range would cause very small austenite grains. The ferrite grains in the plate material would be distributed throughout within the pearlite grains.

In the plate-area that reaches 725°C (1335°F) to 850°C (1560°F), the pearlite grains would transform to austenite, and some of the ferrite would be absorbed into the austenite grains. During cooling, small ferrite grains separate, and at 725°C (1335°F), the remaining austenite transforms back to pearlite. The final structure consists of coarse ferrite grains that had never dissolved and much finer clusters of ferrite and pearlite grains where previously only pearlite had existed.

Influence of cooling rate

The faster the weld metal is cooled, the greater tendency it has to undercool, and the grain size of the solidified weld is smaller. Faster cooling rates also favor the formation of trapped slag inclusions and gas blowholes. Because of the allotropic changes that occur in steel, a cooling rate below 850°C (1560°F) influences the structure.

Very rapid cooling from 850°C (1560°F) to 750°C (1380°F) causes the austenite to undercool rather than transform immediately to pearlite. Because there is insufficient time for the diffusion of carbon atoms required for the austenite-to-pearlite transformation, the massive transformation to martensite occurs instead at about 315°C (600°F). The carbon atoms are trapped in the distorted body-centered tetragonal martensite crystals.

In Figure 2-5-1, the distribution of heat in a plate is described; the lines indicate the typical pattern and distribution of heat from welding on a plate.

The same effect is shown in Figure 2-5-2 in a weld; in this picture, the heat distribution in the weldments is superimposed on an iron-carbon phase diagram indicating the possible effect of heat on various regions of the weldments. Such superimposing is helpful in understanding the effect of heat.

Stresses, shrinkage, and distortion in weldments

6

Because of the unavoidable effects of heat that always accompanies welding, dimensional changes will occur. However, they can be minimized, and often one condition can be used to counteract another.

Weld-metal shrinks upon solidification, but this is not the primary cause of distortion problem in weldments after welding. During solidification, as the atoms of iron in the melt assume the fixed positions in the crystal lattice of growing solid grains, the coupling of the liquid and solid are very weak. Therefore, the weld-metal cannot exert much stress on the adjacent base metal. Solidification shrinkage accounts for dishing or deformation in the weld-metal. It cannot, however, generate sufficient stresses capable of decreasing the overall size of the weldments or pulling a portion of the weldments.

Immediately following solidification, however, the cooling weld-metal continues to contract. This thermal contraction generates stresses up to the yield strength of the material at that temperature in the cooling cycle. This could lead to some very serious damage to the material including possible cracks.

Distortion is deviation from the desired form and occurs as a result of welding because of stresses that develop in the weldments from localized thermal expansion and contraction. Distortion is dependent on the following:

1. The magnitude of the welding stresses developed by localized thermal expansion and contraction
2. The distribution of these stresses in the weldments
3. The strength of the members

Stresses in weldments

Definitions of terms

Residual stress

Residual stress is the internal stress that remains in a member of the weldments after a joining operation. Residual stresses are generated by localized, partial yielding during the thermal cycle of welding and the hindered contraction of these areas during cooling.

Structure stress

Structure stress arises from grain boundaries, crystal orientations, and phase transformations in small volumes of weld-metal.

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Reaction stress

Reaction stress is an internal stress that exists because the members are not free to move.

Stress concentration

Stress concentration refers to the increased level of applied stress that develops at abrupt changes in a section such as sharp transitions, abrupt changes in weld profile, sharp corners, notches, and cracks.

Development of stresses

Moving localized heat source

The local rise and fall in temperature at any point along the weld as the heat source first advances toward a point and then passes it develops stresses and causes changes in the microstructures.

If the metals being welded had zero coefficients of thermal expansion, no stress would develop and shrinkage and distortion would not occur.

But temperature changes do cause a change in volume and because, in welding, the parts are never free to expand or contract in all directions, it is the behavior of steel attempting to expand and contract under conditions of restraint that must be considered.

For nearly all welds started at room temperature, and regardless of the restraint, the maximum tensile shrinkage stress is close to the yield strength.

Distribution of stress in a simple weld

The following sketch describes the stresses built in weldments. With the help of Figures 2-6-1 and 2-6-2, we can understand the effect of heating and cooling in a simple weld. In more complex joints, the stresses are more complex and have more serious implications on the performance of the weldments.

A weld is rapidly deposited along the edge of two pieces of metal. The entire weld zone is still at a high temperature when the weld is completed.

At high temperature, the metal close to the weld attempts to expand in all directions, but it is prevented (restrained) by the adjacent cold metal.

Because it is restrained from lateral expansion (elongating), the metal close to the weld is compressed.

During cooling, the unstable zone attempts to contract once again, and now the cold metal surrounding it restrains it. As a result, the unstable zone becomes stressed in tension.

When the welded joint has cooled to room temperature, the weld and the unstable region close to it are under residual tensile stresses close to the yield strength.

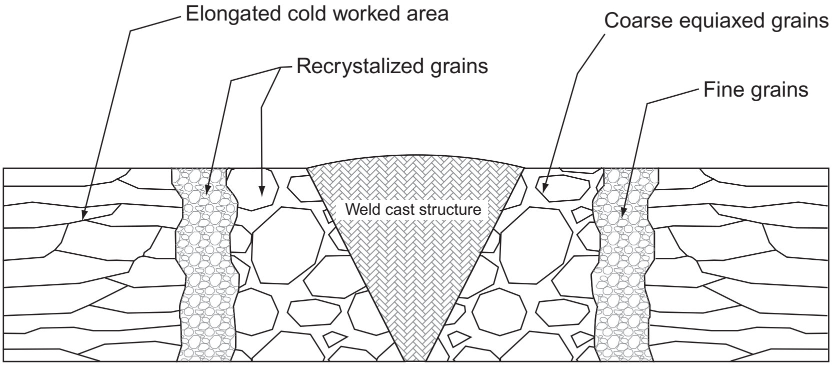


Figure 2-6-1 Stresses in weld.

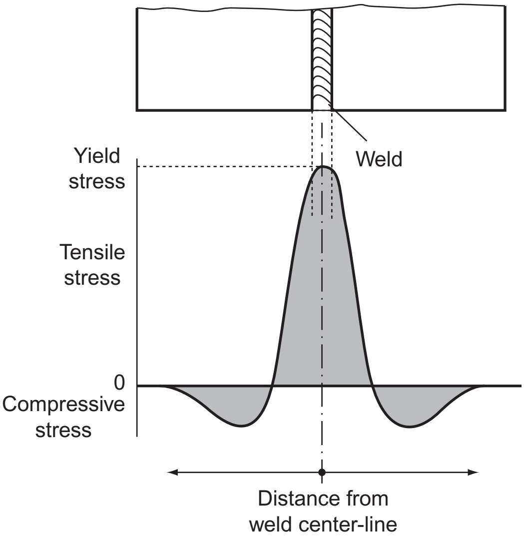


Figure 2-6-2 Stress distribution in weld.

To balance the shrinkage-related tensile stresses developed at the edge, there must be a region of tensile shrinkage stresses opposite of the unwelded edge and a region of compressive stresses between the two tensile zones.

Residual stresses

To calculate residual stresses in weldments, detailed accurate information on the temperature distribution during the welding process must be known. Variations in thermal conductivity and changes in mechanical properties at high temperatures further complicate the calculation.

It is known that stress gradients similar to temperature gradients exist in metal adjacent to a weld. Restraint during welding, such as rigid clamping or even the mass of the structure itself, results in even higher residual stresses. Because the stress system is in equilibrium, externally applied loads cannot add to the residual tensile stresses until the residual compressive stresses are overcome.

If the load does cause a small amount of plastic strain in highly stressed areas, then the peak stresses in those areas will be reduced. Stress relief heat treatment may dissipate residual stresses.

Shrinkages

Shrinkage transverse to a butt weld

Shrinkage perpendicular to the long axis of a weld is called transverse shrinkage. It is primarily dependent on the cross-section of the weld-metal in the joint as well as the thickness of the joint.

The amount of shrinkage varies with:

1. Degree of restraint on the members during welding and cooling.
2. Cross-sectional area of the weld-metal.
3. Extent to which it flows into the adjacent base metal.
4. The number of beads or layers in the weld.
5. Temperature-time cycle of the bead deposition.

Transverse shrinkage is cumulative. For welds made in 25-mm (1-in.) and thicker steel with the shielded metal arc-welding (SMAW) process, an estimating calculation of transverse shrinkage is made using the following relation of base metal thickness, cross-section area, and the root opening of the weld.

$$\text{Transverse shrinkage } (S) = 0.2\,(A_w/t) + 0.05\,(d) \qquad [1]$$

Where:

$S =$ Shrinkage liner inches
$A_w =$ The cross-sectional area of the weld, t is the base metal thickness
$d =$ The root opening (US customary units).

For calculation in SI units, the following equation can be used.

$$S = 5.16 \times A_w/t + 1.27\,d$$

In general, a greater degree of restraint results in less shrinkage and higher residual stress levels.

In practice, it has been observed that welding in the flat or horizontal position allows higher travel speed and decrease shrinkage by up to 20% from other out-of-position welds.

Preheating provides more uniform heating and cooling, and minimizes shrinkage.

Cooling between passes increases restraint and reduces shrinkage.

Although postheating reduces residual stresses and promotes plastic flow, there is no change in the shrinkage that occurred during welding.

Cold peening can counteract transverse shrinkage; however, undesirable side effects of peening must be considered before specifying peening as a control method for transverse shrinkages.

Shrinkage longitudinal to a butt weld

Longitudinal shrinkage is proportional to the length of the weld. Longitudinal shrinkage is also a function of the weld cross-section and the cross-section of the surrounding colder base metal that resists the expansion and contraction forces of the heated weld and base metal (Figure 2-6-3).

A rough estimation can be made using the formula for predicting longitudinal shrinkage when the restraining plate is not more than 20 times the cross-sectional area of the total weld:

$$\text{Longitudinal shrinkage}\,(S) = 0.025\,\left(A_w/A_p\right) \qquad [2]$$

where:

S = Shrinkage in linier inches
A_w = The area of weld
A_p = The area of the restraining plates

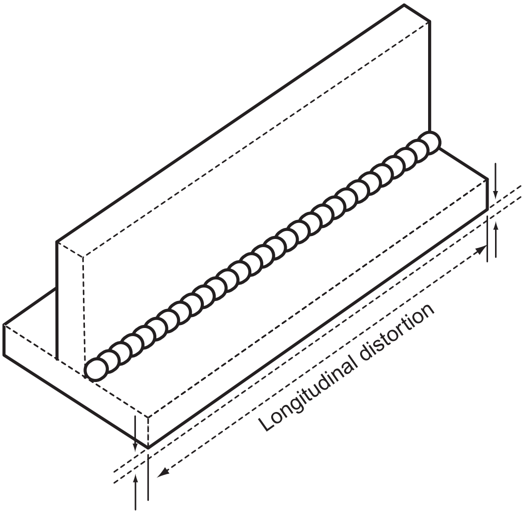


Figure 2-6-3 Longitudinal stress and distortions in weld.

In another approach to the calculation of longitudinal shrinkage (using values in SI units), the following equation is used:

$$\Delta L/L = 3.17 \times I \times L/100{,}000 \times t$$

where:

Δ L is the longitudinal shrinkage (mm)
L is length of weld (mm)
t is the thickness of the plate (mm)
I is welding current (A)

Distortion in weldments

General description

The localized area along which the arc or heat source passes is the starting point of a distortion problem. The temperature differential between the weld zone and the unaffected base metal is great, and much localized expansion and plastic flow take place. Restraint from clamping and the mass influences the extent of plastic flow.

Angular distortion

Angular distortion is the angular change in relative positions of members extending from a weld area as shown in Figure 2-6-1. Note that there is a shorter width of contracting weld-metal at the root of each weld than at the face. This difference in width, which must contract upon cooling, is a major factor in angular distortion.

For single-bevel groove welds in butt joints and T-sections, the angular distortion is nearly proportional to the number of beads or layers deposited in a joint.

Angular distortion can be controlled by following:

Using the minimum amount of weld-metal required.
Depositing the weld-metal in the fewest number of layers.
Avoiding very narrow root profiles and wide faces as much as possible.
Balancing the amount of weld-metal about the neutral axis of the weld.
Presetting the members at a slight angle opposite the location where distortion is expected to develop.

Longitudinal bowing

Longitudinal distortion of long members is caused by shrinkage stress, which develops at some distance from the neutral axis of the member. The amount of bowing is determined by the magnitude of the shrinkage stress and the resistance of the member to bending indicated by its moment of inertia.

Bowing on a long slim member can be roughly calculated in US customary units as:

$$\Delta = 0.005A_w\left(L^2\right)d/1 \qquad [3]$$

where:

Δ = The resulting vertical movement
A_w = The total cross-sectional area within the fusion line of the welds
d = The distance between the center of gravity of the weld group and the neutral axis of the member
L = The length of the member (in.)
l = The moment of inertia of the member

Longitudinal distortion is controlled by balancing welds around the neutral axis of the member. Prebending the member in a bow opposite to that which will develop from welding is often practical.

Buckling

A thin sheet is subject to buckling, which is caused by the inability of a laterally unsupported sheet to resist compressive stress without buckling.

Welding alternately on opposite sides of a part will reduce distortion by neutralizing each distortion.

Corrective measures

The corrective measure for distortions of any kind discussed earlier must be preassessed and weldments designed accordingly. Failing to acknowledge distortions and provide distortion control in a design would often result in very difficult situation during and after the fabrication is completed, which may lead to repairs or even rejections.

These controls include activities during execution, planning, and sequencing of welds including the preheat and postheat treatments, counterallowances for distortions, staggering of the welds, choice of the welding processes control of artificial restraints, etc. Postfabrication correction is always difficult and expensive, and sometimes disastrous for all the efforts and cost incurred in fabrication.

Marginal corrections can be accomplished on some sections of the weldments. The success of the effort is dependent on how restrained and strained the member is that's being corrected.

Application of heat to achieve the correction is one safe method and is often practiced with somewhat limited success. The result of such straightening is dependent on various points discussed earlier, including the inbuilt restraint of the member itself (Figure 2-6-4).

Thermal straightening

Thermal straightening is the deliberate application and controlled shrinking of specific portions of plates or structural members. This is a controlled application of the problem itself to correct the problem, in which a localized area of metal is

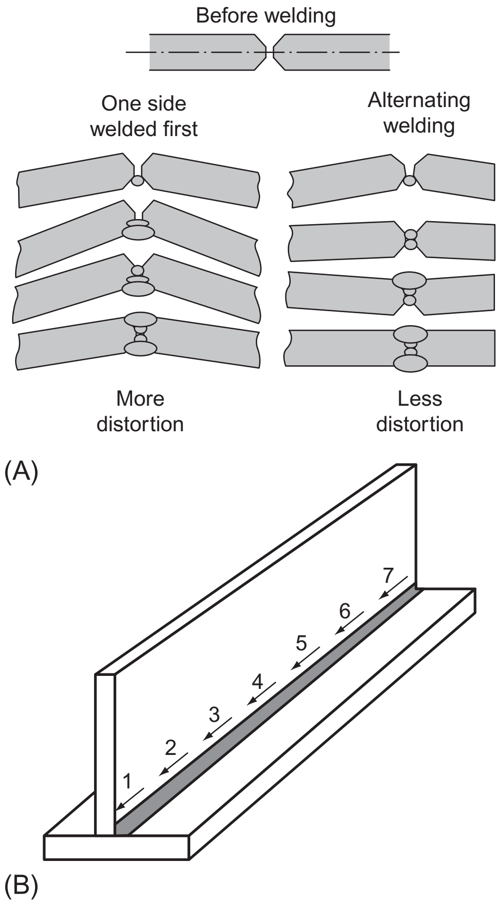


Figure 2-6-4 Controlling distortion by welding. (A) Right: more distortion; Left: less distortion. (B) Sequence of welding to reduce distortion.

torch-heated to a high temperature; for most structural steel, it is within 850–1000°C. During heating, the localized area must expand, but it is constrained by the colder, stronger surrounding metal. Therefore, the heated metal is forced to upset or bulge in the desired direction.

When the localized area reaches a reasonable red heat of 870–990°C (1600–1800°F), heating is stopped to confine the upsetting to the desired area and direction.

Upon cooling, the heated area contracts, but because the upset is not equally reversible during cooling, a net shrinkage results, which pulls the surrounding metal inward. Thus, the movement in this direction will be greater than the movement in the opposite unwanted direction during heating.

This movement is used to control distortion, which occurred earlier during welding or by some mechanical action.

Buckling in a sheet can be removed by heating a localized area in the center. The surrounding metal must be kept cool and preferably restrained. Upon cooling, the central localized spot will shrink and draw the sheet flat.

Designing weld joints

The design for a weld is part of the overall activity of designing the structure. Thanks to the popular television series, everyone understands that a structure is considered as strong as its "weakest link." In a welded structure, or "weldments," the weakest link is often the weld joint. The weld is the weakest link because the weld is not similar in metallurgical structure as the parent metal. Often, an attempt is made to overcome this by either overdesigning the weld or by overmatched weld-metal.

In the following paragraphs, we will briefly discuss some of the factors that need to be considered while designing a weld for successful weldments.

Earlier in this chapter, we discussed stress in welds, and the focus in that part was the stresses caused in metal due to the heating and cooling cycles of welding, and resultant effect on the shape and appearance of the weldments. In this part, we concentrate on the determination of some numerical values of the stress, matching those values with the overall structural requirements.

Assessing the strength of welds

There is a number of factors to consider when designing a structure; one of them is the allowable stress (f) in the members of the structures. When a structural member is constructed or joined to another member by welding, it is imperative that the strength of the weld is also determined as a consideration for integrity of that structure. This will involve a welding engineer to determine, among several other things, the type of material, available resources including the available welding processes, their advantages and limitations, and also what type of weld joint is best suited for the purpose. The options are numerous, for example, to use full penetration welds that may involve V, J, U, or combinations of weld groove preparations, or a lap or a fillet weld, or whether to use continuous weld or skip or stitch weld, etc. This decision will be further affected by the fact that the weld joint may or may not be accessible from both sides. For example, the girth welds in pipeline welding are seldom accessible from the inside, hence a full penetration weld from one side is made. However, similar girth welds in a pressure vessel shell are mostly accessible to back gouge and weld from inside. To understand all this, the terminologies related to weld design must be understood. Given in the following text is some of the terminology that is useful for a welding engineer when designing the welds.

Throat of a weld

The throat of a weld is the effective depth of the weld. In a full penetration weld, it will be the depth of the groove measured normal to the base of the groove. In a fillet weld, it will be at 45 degrees from the root of the fillet to the hypotenuse of the weld. In a right-angle weld (a weld with equal leg length), the 45 degrees will intersect the hypotenuse in the middle; however, this will not intersect in mid-hypotenuse if the leg lengths are unequal. The throat is often denoted as (t_e), meaning effective throat.

Like any structure, for welding, the stresses that need to be considered are tension, compression, and transverse stress (shear). For a butt weld, if the welding consumable selected for the welding would result in a weld-metal that will have tensile strength and ductility that matches the parent metal, then the weld is considered suitable for tensile and compressive load services of the structure.

For fillet welds or members that would be in shear stress, the determination of allowable stress (f) is different from butt welds, and it is calculated as follows.

The allowable stress for fillet or partial penetrated weld is denoted by Greek letter τ, and it is established as equivalent to 30% of the specified tensile strength of the welding consumable used for welding. Using this information, the calculation of unit force per linear inch for a given size of the weld for a given weld-metal can be determined.

If we assume that a given equal leg (ω) fillet weld is 3/16 in. (0.188 in.), and the weld-metal-specified tensile strength is 60,000 psi (E60XX welding electrode), then the allowable shear stress for this fillet weld can be determined as:

$$\begin{aligned} f &= 0.707\omega\tau \\ &= 0.707 \times (0.188 \times 0.30) \times 60000 \qquad [4] \\ &= 2384\ \text{lb/linear inch of the weld.} \end{aligned}$$

or

$$2.38\ \text{kips/linier inch of the weld}$$

This calculation is a simple example. The mechanical strength calculation for all welds would be similar, but the other factors associated with welding will vary significantly, for example, if the weld is in a high-strength alloy, then the effect of preheat and postheat treatment of the weld will have to be considered. This fact highlights the importance of the proper welding procedure specification (WPS), its qualification to establish the mechanical properties, and qualification of welders and welding operators to be able to strictly comply to the qualified parameters so that consistent quality of weld is deposited.

Sizing a fillet weld

The previous calculation can also be used to determine the required size of the fillet weld that would meet the loading stress. If the allowable stress of the structure is known, then it is relatively easy to determine the size of the weld using previous relation of various factors.

The selection of matching strength and suitable welding consumable will be an essential factor in determining the size of the weld.

Fillet welds

As a welding engineer responsible for designing a fillet weld of a size that have the desired load carrying capacity, or how much load the weld can safely lift without failure.

In the absence of such calculations, the normal reaction is to over weld. That is both detrimental to the strength and properties of the material as well as it is a costly exercise. Welding engineers must know and understand the basics of weld design (Figure 2-6-5).

Over-welding is an epidemic in the industry, more on how over-welding affects the cost of welding read "Weld size and cost control" section in this chapter. Over-welding stems from lack of knowledge and understanding about how to size a weld. Unfortunate part of this lack of knowledge and understanding is seen even among engineers that have the luxury of using finite element analysis software, and yet they specify oversized weld. This over-welding can have a tremendous impact on the property of the material that may in future be the cause of failures, and it also increases the welding cost.

Sizing of the fillet weld is an important aspect of weld designing, discussed in Chapter 9 of this section of the book. To determine the required size of the fillet weld, we need to determine the strength of the weld. To explain how to determine the strength of a weld we will start with a simple example, we start with understanding how to determine the strength of a transverse fillet weld. A transverse fillet weld is one that is perpendicular to the force applied as seen in Figure 2-6-6.

Because the load is perpendicular to the weld it is a tensile load. The formula we need to use to determine the load carrying capacity of the weld is:

$$\sigma_t = \frac{F}{A}$$

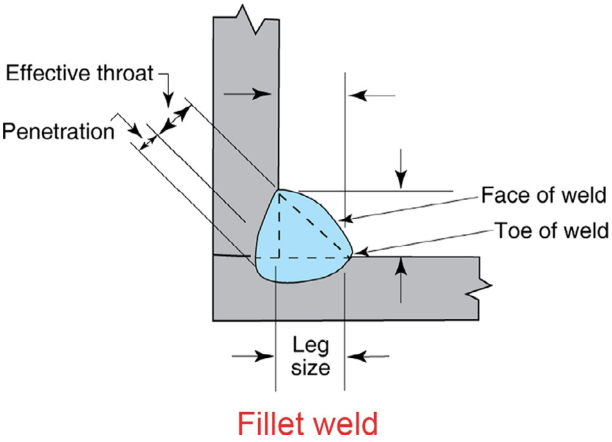
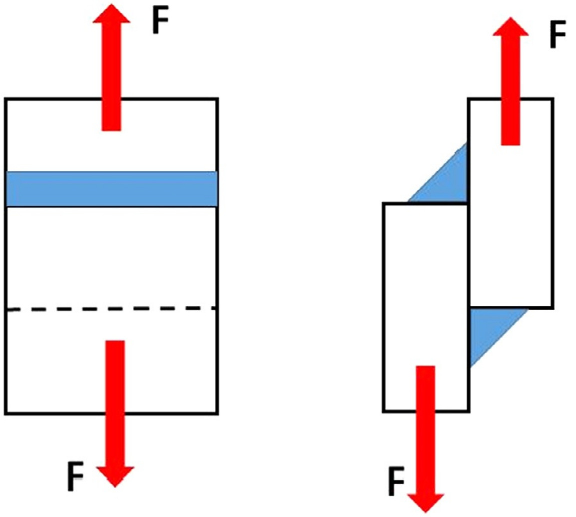


Figure 2-6-5 Fillet weld with weld nomenclatures.

Figure 2-6-6 Transverse fillet weld.



Where:

σ_t is the tensile strength of the weld (determined by the filler metal being used) in PSI.
F is the force the weld can handle, in other words, the strength of the weld in lbf.
A is the effective area of the weld.

The effective area of a weld is calculated by multiplying the length of the weld times the throat of the weld. For design purposes we use the theoretical throat as shown in Figure 2-6-7.

In Figure 2-6-7, the specified equal sided fillet weld leg size is ω. To obtain the theoretical throat we need to factor the given fillet weld size ω by the cosine of the angle of the weld between the base and the hypotenuse of the right angle triangle, which is 45°. So we multiply the specified leg length (ω) of the fillet weld, times the cosine of 45° which is $1/\sqrt{2} = 0.707$. For all fillet welds with both legs being of the same size, the theoretical throat will be 0.707 leg size (ω).

Since we are determining the strength of entire weld the length of the weld also is a factor. The given length of the weld on each side is 10 inch, thus the total length is $2 \times 10 = 20$ inch.

Now we have all data of the weld and can calculate the effective area of the weld. Which is Length × Effective size of the weld.

$$20 \times 0.707\omega.$$

We require one more data to determine the strength of the weld. That is the strength of the weld metal. The weld is carried out using FCAW process using E70T-1 wire. That means the tensile strength of the weld metal is 70,900 psi (Figure 2-6-8).

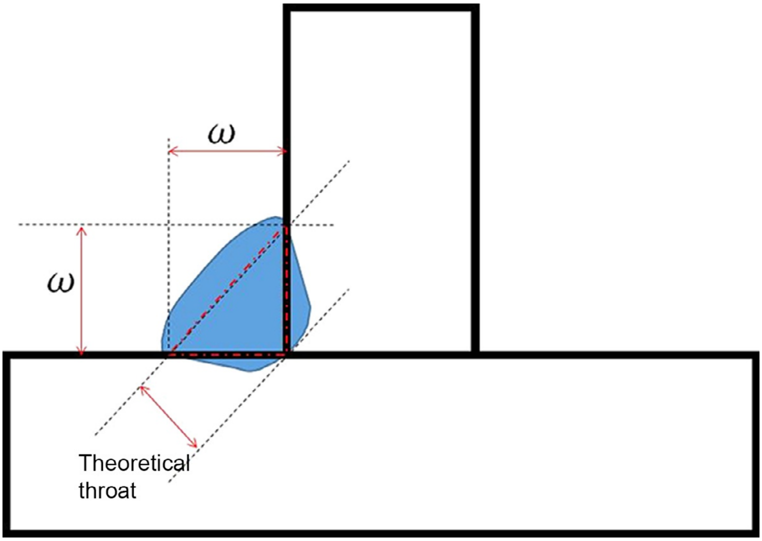


Figure 2-6-7 Theoretical throat of a fillet weld.

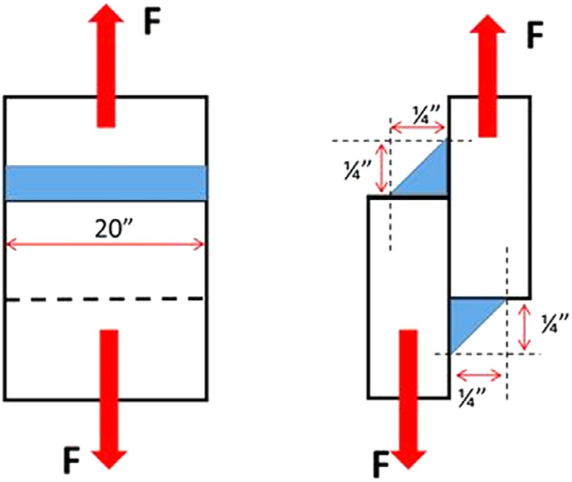


Figure 2-6-8 Fillet weld under tensile load.

First, determine the throat size.

$$\text{Throat} = \omega \cos 45^\circ = (0.25) \times (0.707) = 0.177''$$

Now determine the effective area of the weld. Remember, there are two 10-inch long welds.

Effective Area (A) = 2 × length × throat = (2) × (10) × (0.177) = 3.54 sq. in.

Now we go back to our main formula.

$$\sigma_t = \frac{F}{A}$$

Because we are using an E70T-1 wire, is equal to 70,000 psi. Now we have all the values except for the one we are solving for, F.

We rearrange the formula to solve for F.

$$F = \sigma_t A$$

$F = (70{,}000) \times (3.54) = 247{,}800$ lbf.

So our 20-inch long (total length), double-sided, 0.25-inch fillet welds have a load carrying capacity able to withstand a tensile force of almost quarter a million pounds. Now that is lot of strength and it can lift a lot of weight.

However there are several conditions to this seemingly extreme strength, for example, the following.

- If the lifting force is applied rapidly the weld would fail at a significantly lower load.
- If the force is not applied perfectly evenly along both welds the welds would fail at a significantly lower load.
- If there are any weld discontinuities such as cracks, craters on undercut, the welds would fail at a significantly lower load.
- If the load is not perfectly static, the welds would fail at a significantly lower load.
- If the load is not perfectly perpendicular to the welds, the welds would fail at a significantly lower load.

The list of “ifs” keeps growing, and due to these unknown factors, welding codes introduce a factor of safety. Factors of safety are used to ensure that the structures are not over loaded. The factor of safety tries to cover all the Ifs, especially among them is the weld loaded in shear. The shear load is essentially the worst case scenario and it limits the maximum force that can be applied to a weld before it fails. Most of the design is done with the assumption that fillet welds will be loaded in shear.

Let us now consider the fillet weld strength in shear.

If the load applied is not perfectly perpendicular to the fillet weld, the weld is under shear stress, and its load carrying capacity is significantly diminished. Because of this reason, welds are always assumed to be loaded in shear (Figure 2-6-9).

In this case the applied load is parallel to the welds. The forces are pulling the members being joined in opposite directions, which places the welds under shear. When a weld is in shear we can no longer use the tensile strength of the weld—from the used filler wire or electrodes—to determine the strength of the weld. Instead, the weld-metal tensile strength is reduced by a factor in order to assure safety. AWS D1.1 The Structural welding code, requires that the minimum tensile strength of the filler metal be multiplied by 0.30 to obtain the allowable shear stress on the weld.

The calculation is the exact same as when calculating the strength of a transverse fillet weld, except for the safety factor. The notation now shows the maximum shear stress (τ) allowed rather than the maximum tensile stress (σ).

$$\tau_{allowable} = \frac{F}{A}$$

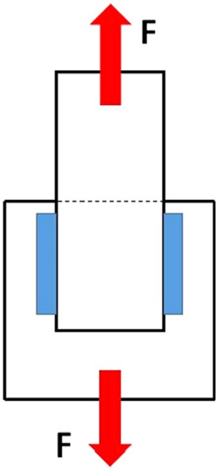


Figure 2-6-9 Fillet weld in shear load.

Where,

$\tau_{allowable}$ is the maximum allowed shear stress on the weld.

F is the force the weld can handle, in other words, the strength of the weld in lbf.

A is the effective area of the weld.

Notice that instead of “tensile stress” we now have “allowable shear stress”.

The weld is made with an E70T-1 filler metal with minimum tensile strength of 70,000 psi. There are two 20-inch long lap welds on both sides of the joint (Figure 2-6-10).

The allowable shear stress for the welds would be 70,000 psi × 0.30 = 21,000 psi. A reduction of 70% compared to the case where the fillet weld was in pure tension.

The leg length of the fillet weld is 0.25 inch, then the shear strength—the load carrying capacity of the weld is calculated as follows.

To solve the F (force that is the shear-strength of the weld) the above discussed formula is suitably rearranged, as following.

$$F = \tau_{allowable} \times A$$

We know that the allowable shear stress is $70{,}000 \times 0.30 = 21{,}000$ psi.

The theoretical throat size is $0.25 \times 0.707 = 0.177$.

Thus the effective area of the weld (A) = $(2 \times 20) \times 0.177 \times 2 = 7.08$ sq. in.

The value of force F we get is $F = 21{,}000 \times 7.08 = 148{,}680$ lbf.

This fillet weld can safely (support) lift a load of 148,680 lbf.

Stress causing fatigue in weld

The performance of weldments under cyclic conditions is an important consideration in design and fabrication of structural members. Several examples of fatigue can be sighted from common occurrences: the bridges over rivers carrying cars and trucks,

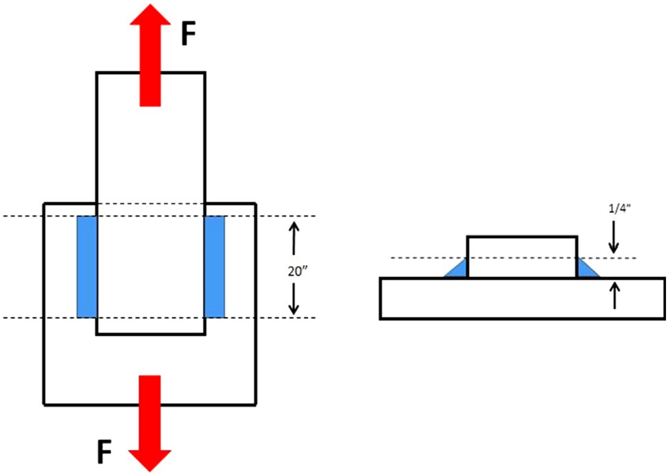


Figure 2-6-10 Fillet weld in shear load.

overpasses on highways, railroad and railroad bridges carrying freight trains and passengers. The fatigues caused in industrial equipment that go through several heating, cooling, and pressure cycles also go through fatigue stress in metals and welds of these equipments. Fatigue failure at normal working stresses is generally associated with stress concentration. The fatigue stress is a major cause of concern for offshore deep-water structures and risers. The welding procedures qualified for these applications are tested to meet these stresses.

The welding process and procedures are carefully selected to avoid any undesirable and abrupt changes in the weld-metal. The factors to consider in such evaluation are not only if the weld-metal matches in tensile strength or the weld in a current condition meets the specified quality but also to ensure that the weld is sound enough to address the following important issues during the designed life of the structure:

- Full penetration of weld
- Welds with no stress risers (e.g., undercuts, notches, lack of fusion, excess penetration, abrupt transition in weld profile, the angle at which the weld profile merges with the parent metal, etc.)
- Weld-metal ductility and hardness control both in weld-metal and heat-affected zone (HAZ)
- Weld-metal yield-to-strength ratio, in relation with the parent metal YS/TS ratio
- Crack propagation
- Crack arrest properties
- Acceptable level of defects and their interaction under stress
- The service environment and its long-term effect on properties of the metal, especially on hardness of base metal as well as weldments

For a given material, the calculation of maximum allowable stress-causing fatigue stress in a given life period is dependent on the ratio of minimum and maximum stress (K).

This relation is expressed as:

$$\sigma \text{ max} = \sigma_{ST}/1 - K \tag{5}$$

where K is the ratio of minimum and maximum stress and σ_{ST} is the stress in a steady-state.

The allowable stress should not exceed the steady stress for the parent material. However, the stresses that cause fatigue failure are more complex and cannot be calculated by the previous equation. This complexity is explained by the variables discussed further.

The effect of the weld profile contact angle with the parent metal is plotted on the graph described in Figure 2-6-11, where the contact angle is on the x-axis, and the fatigue cycle 2×10^6 in MPa (KSI) is on the y-axis. We note that the plain plate has much better resistance to fatigue than the welded joint, and the stresses continue to rise with increasing degree of contact angle. It may be empirically stated that the contact angle of less than 20 degrees is better suited for designing fatigue resistance weldments.

It may be noted that planner defects in the weld increase the possibility of fatigue failures, whereas rounded indications like porosity and inclusions do not have major contributions to the fatigue crack propagation. In fact, it has been shown in several experiments that porosity has been able to resist and control the growth of propagating cracks. In this context, it is important to note that inclusions longer in length and closer to the material surface are to be considered as contributing to the crack growth as compared with rounded inclusion. The depth of these discontinuities is also a factor in their contributing or resisting the growth of fatigue cracks. The deeper defects are, in fact, compressed under the stress and often reduce in size, thus are not able to help propagation of cracks.

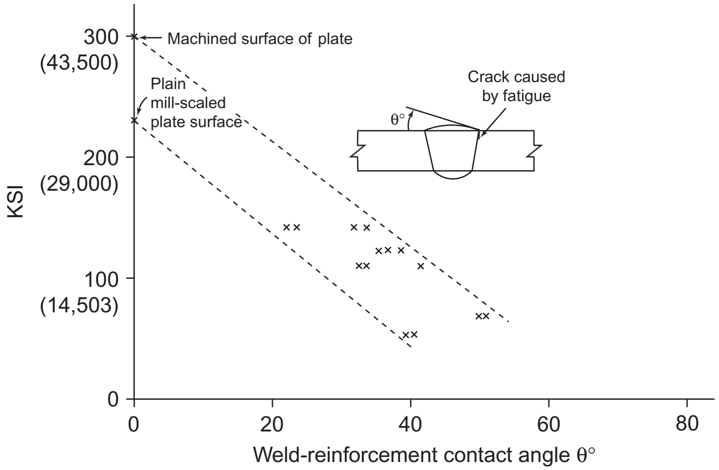


Figure 2-6-11 Effect of weld reinforcement contact angle on fatigue strength of weldments.

Fracture mechanics help determine the relationship between the stress and the critical discontinuity size. The size of the imperfection would propagate under plain strain conditions. It is established that the critical discontinuity size is inversely proportional to the square of the applied stress ($S = 1/\sigma_{\text{applied}}$). The geometry and location of the discontinuity assumes critical importance in determining the relationship between the stress and size of discontinuity. In this process, the depth-to-length ratio plays an important role, and valid plain strain or elastic-plastic fracture value is required to determine the combination of stress and discontinuity size at which a structure can be safely operated.

The existence of plain strain at the tip of the discontinuity is essential for a discontinuity to be an initiator of crack. Thus cracks, incomplete fusion, or lack of penetration are the key discontinuities that contribute to cause brittle failure. Porosity and slag inclusions are generally not contributors to such failures. Fracture mechanics allow us to analyze the critical crack size for unstable crack growth leading to fracture. Crack tip opening displacement is one of the common methods to determine the growth of crack leading to fracture. In this process, the tip of a sharp crack is loaded under plain strain conditions; if the stress intensity factor denoted with letter K exceeds the critical stress intensity factor K_{IC}, then the crack becomes unstable and propagates, leading to failure of the member. The relationship of the stress (σ), stress intensity factor K, and the crack length (a) are described in following equation:

$$K_1 = C\sigma\,(\pi a)^{1/2} \qquad [6]$$

where:

C = a constant depending on discontinuity size and shape

In engineering critical evaluation (ECA) of weld for fitness for service evaluation, and to determine the acceptable size and shape of discontinuity, some assumptions based on empirical experiences are made; these are listed and explained in the following:

- The plain strain fracture toughness of the material K_{IC} is predetermined.
- The critical size for unstable fracture is determined from the prior equation.
- The worst case is assumed, which is the weld discontinuity is a crack.
- The vector sum of the applied and residual stress is estimated.
- A margin of safety is applied, and maximum allowable crack-like flaw is selected.
- Acceptance criteria for more innocuous discontinuity are defined.

Fatigue tests are carried out to determine the behavior of material and, from welding engineers' perspective, the behavior of flaws in any weld under stresses causing fatigue. Several tests are involved in determining fatigue behavior. The process may involve introducing stresses to develop fatigue in the member and then determining the growth of the weld flaws; both buried and surface opening flaws are tested. A number of mechanical tests discussed earlier in the section is involved, including hardness test and fracture toughness testing of welds. In welds, the method is used to determine the opening mode plane strain fracture toughness (K_{IC}), the critical crack tip opening displacement (CTOD), fracture toughness, and critical *J* fracture toughness of the material. The weld is precracked at the specific location and tested in displacement control under quasistatic loading and at a constant rate of increase in stress intensity factor, which is within the range of 0.5–3.0 MPa ms$^{0.5-1}$ during the initial elastic deformation. The method is useful in determining the ductile to brittle fracture behavior under decreasing temperature.

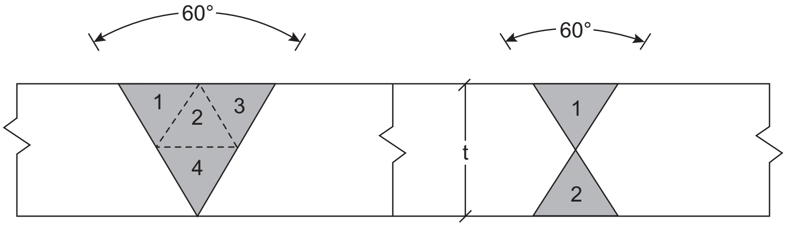
In another fatigue testing of pipes, often for offshore deep-water steel catenary risers (SCRs), a full-scale fatigue testing method of resonance testing machines is used, in which a rotating bending moment of constant amplitude is applied at the resonant frequency of the pipe, typically between 25 and 30 Hz, allowing high-cycle testing of riser girth welds. The system is used for up to 200 million cycles.

Weld size and cost control

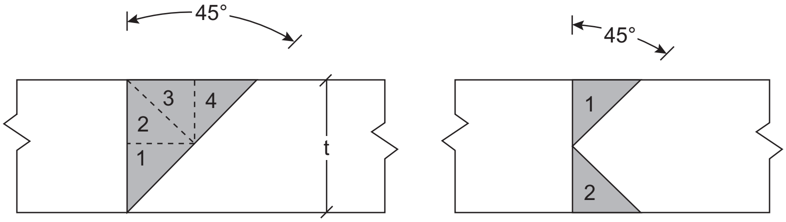
Welding cost analysis involves taking measure of the weld design, welding process selection, and preparation, labor, and material. Several commercial software are available to calculate the cost of welding, which inputs all the data and spits out the cost estimate. However, most visible and known factors, though not most expensive, are dependent on consumption of various welding consumables, top among them is the consumption of welding filler metals in the form of filler wires or electrodes. The control on cost of electrode filler wire consumption can make a significant difference in profit or loss of the project. Another side effect of overwelding is not so much the cost of the consumable but rather possible stresses that may lead to premature failure of weldments, as well as metallurgical changes in the material affecting performance of the weldments.

The factors to consider in designing a weldment is the cross-sectional area of the weld. The weld cost is directly related to the cross-section of the deposited weld-metal. While controlling the weld-metal volume, it must be noted that too-narrow weld may be a cause of poor quality of the weld, in the form of shrinkage cracks or cracking issues involved with weld depth-to-width ratio (W_D/W_W) especially in high-heat welding processes, higher strength material, or a combination of both. Increasing the cross-sectional area of the weld has a direct impact on the cost; it also has an impact on the quality of the weld. A well-balanced compromise between these two extremes is required. A small groove angle in steel for thickness ≥ 16 mm (0.630 in.), and a choice of double-groove welds is the best approach. In the sketches in Figure 2-6-12, the effect of the changes in the joint design is highlighted. Note that the change in the groove angle significantly reduces the weld cross-sectional area, requiring lesser weld-metal. Similar is the effect of design changes made from single-V groove to double-V groove. A welding engineer, when designing weldments, must weigh in these options and consider what's best for the project.

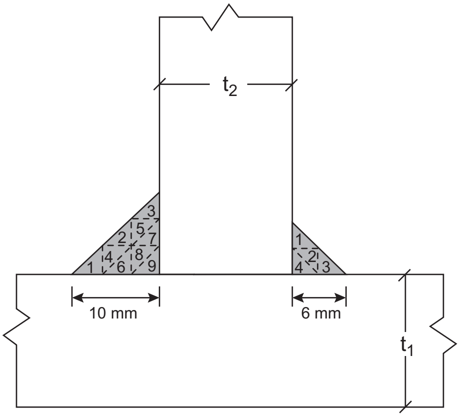
In this regard, it is also important to evaluate the effect of the size of the weld, especially that of fillet welds. It is common practice, mostly due to ignorance and poor understanding of welding, to overweld or oversize a fillet weld. The effect of



Single vs double "VEE" groove



Single bevel vs double bevel groove



Effect of oversized fillet weld

Figure 2-6-12 Effect of over-sized weld. Note the number of equal area triangles in each comparisons above.

oversizing is illustrated in the following sketch where we can easily see that a change in welding size dramatically increases the amount of deposited weld-metal. It may be noted from the sketch that the specified weld size is 6 mm and the overdeposited weld size is 9 mm, an increase in size by 50%. This change in size will require that the deposited weld-metal be increased by twice as much as required by the originally sized weld. Such cost escalation can easily turn a profitable project into a loss-making project, as such overrun of cost is not estimated in the project. This emphasizes the need for control of the weld size to the one designed.

The accessibility to the weld joint is another important factor to consider while designing weldments. Often, a practice of providing a “weld access hole” is followed when a weld is designed in a very tight location. These access holes are sized in such a way to allow for proper clearance that would allow for deposition of sound weld-metal. The welding engineer responsible to design such weldments should be able to recognize the need for these access holes and decide on the minimum required size of the hole. Such decisions must take into consideration how the size of hole would affect the maximum net area available in the connected base metal and must compensate for any loss in the effective strength.

Equally important is the proper selection of material for fabrication. A balance with the designed strength requirements and availability is to be established. A material, however versatile in theory for a specific project, may be too expensive if not easily available.

And last but not least, an important step in cost control is the selection of a suitable welding process, especially the fact that available resources must be made best use of; optimizing the use of available resources and designing around those equipment and resources will keep the cost of welding low.

These are the general guidelines and may be used to best assess the specific conditions on the basis of actual project conditions. Ignorance of or ignoring these points for a cost-effective fabrication is not an option for a successful welding engineer.

Control of welding stresses to minimize through-thickness failures

Base metal through-thickness loading, especially by welding stresses, is a very important factor that a welding engineer must consider when designing. The weld joins that are in “T” and corner joint configurations are especially subject to such loading and likely to fail due to through-thickness stresses. The functions of these type of joints is to transmit normal stress to the surface of a connected part, especially when the base metal thickness of the branch member or the required weld size is equal to or exceeds 20 mm (0.75 in.). Such configurations must receive special attention while designing. The base metal selection and detailing of the weld joint are important factors to consider. Joint details, which minimize stress intensity on base metal through-thickness direction, should be used. Control of the specified weld size discussed earlier assumes critical importance in such designs. Control on stress is of utmost importance in avoiding through-thickness failures of any member of weldments.

Welding of carbon steel and low alloys

The welding of carbon steel and low alloys is the most common welding activity. The wide range of design possibilities exists with these materials. Various grades of material under this general description make this group the most used engineering material. The application ranges from simplest to most complex design structural and component applications.

The approach to welding and its quality varies throughout its application spectrum. A weld in the automobile industry is not put to the same design and quality requirements as a weld joint for bridge construction, or a weld joint for building construction, or a weld joint for a deep-sea structure, or pipeline. They all have their specific importance and specific demands; however, they are not the same.

Carbon steel and low-alloy steel welding for a welder and welding operator might be the easiest ones to accomplish, but they are very dependent on the knowledge of steel metallurgy, more specifically, the knowledge of steel behavior as it cools from molten stage to solid stage and to ambient temperature and beyond, during the welding operation.

Depending on the application of steel weldments, steel metallurgy, and thickness of members being joined by welding, the welding procedure requirements can vary significantly. Requirements are reflected in the demand for various types of preweld preparations, during the weld controls, and postweld treatments and testing results. I have grouped these in groups for understanding; some of these requirements can be listed as shown in the following.

Group 1—Steel Metallurgy

For the purpose of welding only, steels can be grouped in several subgroups based on general compatibility for welding. For example, various welding specifications group several steels and give them a common identification name, which allows for one welding specification to be used for various steel grades. ASME Section IX calls them P numbers; identification P-1 is for a majority of carbon steel and low-alloy steels. Similar grouping and classifications are practiced in AWS D1.1, API 1104, CSA B 51, and various other specifications.

The thickness of the members being welded are also covered in this group due to the complex effect of heat transfer and cooling rate associated with thickness that affects the metallurgical behavior and performance of the steel.

Group 2—Weld Preparation

- Weld joint design preparations
- Weld design types; this would include butt welds, partial penetration welds, fillet welds, etc.
- Weld design dimensional tolerances, bevel angles, and land thickness.

Group 3—Weld Edge Preparation

- Square butt welds
- V-groove
- Double-V grooves
- J-groove
- U-groove
- Single or compound bevels, etc.,

Group 4—Preweld Requirements

- Preweld cleaning
- Selection of right consumables, welding wire, welding electrode, shielding and/or purging gases if used, etc.
- Polarity of current being used

- Tolerances on alignment of weld edges to be welded
- The temperature of the metals being welded at the start of weld process, which is also referred as the preheat of the weld

Group 5—Controls During the Welding

- Temperature controls
- Electrical parameters control, amperes and voltages used
- Weld travel speed or wire-feed speed
- Preheat temperature methods and controls
- Interpass temperature and its maintenance

  Like preheat, this is a metallurgical activity whereby cooling rate and structural changes in the material are controlled.

Group 6—Postweld Controls

This would include metallurgical control wherein the different heat treatments can be given to the material to achieve desired properties. These could include:

- Removal of stresses caused due to fabrication and welding
- Restoration of desired grain structure in the welded material
- Inducing specific properties in the weldments, for example, annealing, hardening, normalizing, etc.

Although these are discussed in this section of the discussion of carbon steel and low-alloy welding, some of the points are equally relevant to welding of any other material. In the following paragraphs, the challenges to welding carbon steel and alloy steel associated with few specific service conditions are discussed. This discussion is to highlight the challenges that a welding engineer may face in their practical lives.

Developing a welding procedure or a welding strategy for carbon steel

In welding of carbon steel, the potential for increased hardness leading to cracking is always a possibility. But there are ways to generalize the possibilities and apply suitable precautions in developing a welding procedure. Almost all arc-welding processes can be used for welding carbon steels. The material's sensitivity to hardenability, cracking, and porosity must be considered in selection of the process, the weld consumable, and heat control as discussed in relation with each group and subgroup in the following section.

Carbon steels can be classified into three distinct groups: low-carbon steel, medium-carbon steel, and high-carbon steel.

Welding low-carbon steels

The low-carbon steels have carbon content of up to maximum 0.15%; they may contain up to 0.5% Mn and some silicon and copper with some impurities. These steels are aluminum killed and produced by continuous casting process. These steels are often available in cold rolled and annealed condition and in the form of flat products like sheets and strips. These steels cannot be hardened by a welding process. This group of low-carbon steel with absence of oxygen in them (killed) are easy to weld, and there is nearly no possibility of hardening and cracking of welds.

The second group of low-carbon steels are those that contain carbon greater than 0.15%–0.30%. These steels are also easy to weld but have slightly higher possibility of hardening if they contain higher manganese. The steels are hot-rolled structural steels in plate and tubular forms. They are killed steel, and because they are hot rolled, they often are covered with scale (iron oxide), which must be cleaned prior to welding. This requires that some additional precautions must be taken during welding if any of the following conditions exist:

- Higher Mn (> 0.5%) content
- Thicker sections
- Joint restraint
- Removal of surface scale before welding (cause of porosity in welds)

Welding procedures for such steels should consider preheating of the joint to reduce the cooling rate of the weld and HAZ.

Some of this group of steel may come in heat-treated conditions like quenched and tempered (Q&T), or normalized. Such steel would require careful selection electrode for producing matching weld-metal chemistry. Controlled welding heat input is essential to prevent diminishing the HAZ properties of the steel. For heat-treated steel, a postweld heat treatment may be necessary.

Welding medium-carbon steels

The medium-carbon steels have carbon content of 0.30%–0.60%, and they may contain manganese (Mn ranging from 0.6% to 1.65%). This makes these types of steel susceptible to hardening during welding. However, they can be very successfully welded with some precautions. They are often available in heat-treated condition such as Q&T for machined products like shafts, couplings, gears, axels, crank-shafts, rails, etc.

Due to the higher carbon and manganese, the formation of martensite is always a possibility in the weldments of this group of steel, which increases hardness and possibility of postweld cracking. To control martensite formation and limit hardness, preheating and postweld heat treatment (PWHT) is almost inevitable.

The welding procedure should select a low-hydrogen process or welding consumables to reduce hydrogen-induced cracking (HIC) of welds and HAZs. Steels of this group that are on the higher ends of alloy content, which increases the steel’s strength, may require a specially alloyed electrode for welding to prevent weld and HAZ cracking. Preheat before welding and PWHT are almost always recommended.

Welding high-carbon steels

The high-carbon steels contain carbon from 0.60% to 2.00%, and this group of steel is very difficult to weld, as they readily enter the hard and brittle martensite phase, as the steel cools from welding.

The primary use of this type of steel is cutting tools, springs, and abrasion-resistant components, which are less likely to be welded but sometimes are. Among the welding steps is the selection of a low-hydrogen electrode for the welding process with very controlled heat input, preheating, and monitoring of interpass temperature followed with a PWHT is part of the carefully developed WPS. To reduce the risk of HIC, the use of austenitic stainless steel electrode is recommended; however, it must be kept in mind that the resulting weld-metal may not match the strength of the parent metal.

Some grades of high-carbon steels are developed for the ease of machining; they contain higher levels of silicon (Si) and phosphorous (P). Such steels are very difficult to weld as they crack and develop porosity.

Welding challenges associated with reducing environment

The reducing atmosphere, also known as **reduction atmosphere**, is an atmospheric condition in which oxidation is prevented by removal of oxygen and other oxidizing gases or vapors, and which may contain actively reducing gases such as hydrogen, carbon monoxide, and gases that would oxidize in the presence of oxygen, such as hydrogen sulfide.

When materials are subject to a service environment that contains reducing agents, there are possibilities of changes in the properties of material. This is especially true for carbon and low-alloy steels, although other materials are not totally immune from such phenomenon.

In such environments, there is ingress of hydrogen in the steel and welds that cause different types of changes in the material and welds. Speaking in very general terms, these changes can be determined by the increased hardness of the weld, HAZ, and the material itself. This increased hardness can and often is the cause of premature failure of the weldments.

The ingress of hydrogen is in two very distinct manners, and each of these is in itself a subject for detailed study. The two types of hydrogen-related cracking are:

1. Ingress of hydrogen during welding
2. Ingress of hydrogen in a process environment

We shall briefly introduce these two phenomena, although as stated before, the two subjects are very elaborate and would require very detailed discussions to include in this book.

Ingress of hydrogen during welding

This occurs during welding and is dependent on several factors including:

- The cleanliness of weld area

  The cleanliness of weld surfaces can never be overemphasized; the presence of moisture on the steel surface, grease, dirt, paint hydrocarbons, and any other material can burn during the welding and disassociate to release hydrogen, which enters the molten metal and gets trapped when the weld solidifies. In the simplest form, this trapped gas is shown as porosity in welds. These can be easily detected through the radiographic examination of welds.

The failure mostly in the form of cracking of the weld or HAZ occurs due the presence of gas porosity, in most cases, the entrapment of hydrogen. These failures are dependent on the stress in the weldments, the hardness of the material being welded, and subsequent service environment of the weldments.

To prevent inclusion of unwanted hydrogen in the weld, it is good practice to thoroughly clean the weld surface and some material in close vicinity of the weld. The maintenance of a clean weld surface during the entire welding activity is the best practice.

- The selection of welding consumable

The welding consumable itself can release hydrogen during welding, which can enter in the weld and develop porosity in the welds.

The contaminated welding fluxes, used in the submerged arc welding (SAW) process, are improperly treated, baked, or heated electrodes and fluxes are the primary cause of hydrogen ingress in the weld. Similarly contaminated with moisture and other elements in welding, gases have similar effect on welding.

Welding wires not stored and handled with care and cleaned prior to use can have similar effect on the weld. Welding wires that show signs of corrosion must be discarded or cleaned as specified by the manufacturers.

The consumable could be the welding electrode used in a SMAW process. There are welding electrodes that generate hydrogen due to its coating. The cellulose-coated electrodes give hydrogen in the weld as high as 60 mL/100 g of deposited weld-metal. These are very heavy amounts of hydrogen in the weld, but the use of such electrodes is very common and essential requirements in certain welding, like welding of pipeline. These electrodes are coated with cellulose to achieve specific properties very essential for pipeline welding. But good engineering decisions will be to either avoid or limit the use of these consumables beyond availing the very essential properties of cellulose welding electrodes.

For critical applications, low-hydrogen welding processes should be used where the hydrogen is limited up to 16 mL of hydrogen per 100 g of deposited weld-metal. Processes are able to give welds with 4 mL/100 g of welds. There are welding electrodes for the SMAW process that are capable of giving welds with <4 mL/100 mg of hydrogen in the welds.

The following welding processes are deemed low-hydrogen processes as they are capable of producing welds with $\leq$16 mL/100 g hydrogen. The only condition is that they follow the cleanliness and avoid the contaminated weld surface, and that contaminated consumables are not used.

- Submerged arc-welding process (SAW)
- Gas tungsten arc-welding process (GTAW)
- Plasma arc-welding process (PAW)
- Gas-metal arc-welding process (GMAW)
- Shielded metal arc-welding process (SMAW) (noncellulose electrodes only)
- Flux core arc-welding process (FCAW)

The previously discussed phenomenon is specifically associated with the welding activity of materials, especially affecting carbon steel and alloy steels.

Ingress of hydrogen in process environment

In process industries, there are several conditions that either contain or react in the process conditions to produce atomic hydrogen. The atomic hydrogen defuses into the steel including the weld. This phenomenon of the atomic hydrogen ingress is significantly different from the inclusion of molecular hydrogen in the weld in the form of porosity, as we discussed in the section earlier.

The ingress of hydrogen in steel manifests itself in different ways, and the industry has given each of them very specific names and acronyms; some of them are listed in the following as an introduction to the subject.

- Hydrogen blistering
- Hydrogen-induced cracking (HIC)
- Stress corrosion cracking (SCC)
- Stress-oriented hydrogen-induced cracking (SOHIC)
- High-temperature hydrogen attack (HTHA)

The object of this discussion is to discuss the challenges associated with these issues and not delve into the various modes of failures that ingress of hydrogen in steel can cause.

The ingress of monatomic hydrogen in steel causes the steel to increase in strength, which is indicated by the increased hardness. It is a serious concern for welding these hydrogen-charged steels. Welds and HAZ are susceptible to cracking as the weld cools. It may be noted that the molten metal has nearly unlimited capacity to absorb hydrogen, but its ability to retain the absorbed hydrogen is very limited. This is the cause of cracking as the weld-metal and surrounding metal starts to cool. Depending on the strength of the steel, there is possibility of metal to crack much later after cooling, a phenomenon often referred to as *delayed cracking* or *delayed hydrogen cracking*.

A suitable welding procedure has to be developed, which will include the following:

- Removal of a significant amount of hydrogen from the charged steel prior to welding
- The control on welding parameters
- Maintenance of heat during welding (preheat, interpass temperature, heat-input, etc.)
- Rate of cooling. The concept of $t_{8/5}$ is introduced here, as the concept relates to the time required to cool the weld-metal and HAZ from 800°C to 500°C. This is related to the directional heat flow in the weldments. The subject of heat flow and cooling rate is addressed in more detail in Section 2, Chapter 2, of this book.
- Suitable postweld heat treatment
- Inspection and testing to establish the required properties of weld HAZ and the parent metal

There are various guidelines specific to the industry that should be referenced in this aspect, for example, the NACE and API have various recommended practices or standard practices that are very helpful in this aspect. The NACE SP 0472 details the methods of control to prevent in-service cracking associated with environments; similarly, API recommended practice 941 is dedicated to steels in hydrogen service in elevated temperatures and pressures. This specific document addresses the subject of HTHA and is based on years of industry experience reported from all over the world. The API includes nomographs copyrighted in 1967. This graph is often referred to as Nelson's Graph after G.A. Nelson who created it in early 1950s. This graph is regularly modified and includes data for various alloy steels and carbon steels used in refinery and petrochemical service with historic data of failures. The readers and students interested in these subjects should reference the latest version of these and any other related documents for guidance.

Welding and fabrication of low-alloy steels

Low-alloy steels present specific challenges with welding and fabrication. The complexity of the weldability is as varied as the alloy steel composition and its application. Each alloy combination presents its own weldability challenge, and they must be treated as such. There cannot be "one size fits all" solution in these cases. What can be generalized is the fact that each of these grades and even the modified versions requires full knowledge of their metallurgical structures and that must be matched with the service demands on those materials after the welding is completed. This requires that the preheat interpass temperatures and PWHT are very carefully considered and strictly followed. Steel with 9% chromium and molybdenum is one such steel that is often used in industrial and heat exchangers' construction. Very carefully developed welding procedure with well laid-out heat-control plans to prevent formation detrimental phase in steel is required to have a successful weldment.

A case study on the weldability of Challenges of 9-Chrome-Moly and Microalloyed 9-Chrome steel.

Case Study 2 Welding and Fabrication of Low-Alloy Steels

Challenges of 9-chrome-moly and microalloyed 9-chrome steel

The use of suitable material for progressively changing design of a power-generating unit has been always a challenge. In the early days, it was the selection of proper material for what today can be termed a low-temperature and less efficient system.

Luckily, that is not the situation now. With demands for more efficient systems and the development of alloys and knowledge of their performance and behaviors in varying stress and temperature ranges, more efficient systems can be operated with minimum downtimes for repairs and maintenance. The key is the understanding of these materials both by designers and the maintenance managers. I have excluded welding engineers from the group because, most of the time, their knowledge is not in question, and often welding engineers are not the final decision makers.

A "combined cycle power plant" is described as a combination of gas turbine generator (Brayton cycle) with turbine exhaust waste directed to a heat boiler and steam turbine generator (Rankine cycle) for the production of electric power. If the steam from the waste heat boiler is used for process or space heating, the term “cogeneration” is the more appropriate term to use, meaning simultaneous production of electric and heat energy. Most of the newer plants are designed as or upgraded to Co-Gen.

The simple cycle gas turbine generators operated as an independent electric power-producing unit. The system is a relatively inefficient process because its net heat efficiency at full load is more than 15,000 Btu per kilowatt-hour. Consequently, simple cycle gas turbine generators are used only as a standby unit or, in some applications, as a supplementary power unit. The fuel economy of such units is of small importance.

Typical heat recovery steam generator (HRSG) types and layout configurations can be listed as following:

- D-frame evaporator
- O-frame evaporator
- A-frame evaporator
- I-frame evaporator
- Horizontal tube evaporator
- Economizer configuration

A gas turbine releases large quantities of gas through its exhaust system; the temperature of these released gases is more than 480°C (900°F). In a combined cycle system, these gases are piped to operate a waste heat boiler. These boilers generate high-pressure steam. This superheated steam is then piped to a steam turbine generator. The resulting “combined cycle” heat rate is in the range of 8500–10,500 Btu per net kilowatt-hour, which is less than a simple cycle gas turbine generator.

A typical combined-cycle system may have either a single-shaft or multishaft configuration. A single-shaft system consists of one each of gas turbine, steam turbine, generator, and HRSG. The gas and steam turbines are coupled to a single generator on a single shaft in a tandem arrangement. The single-shaft arrangement gives operational simplicity, smaller footprint, and lower startup cost, but they are less flexible and have lower functional reliability.

Multishaft systems have more than one gas turbine-generator and HRSG, which supply steam through a common header to a separate single steam turbine-generator.

The efficient design and operation of these combined cycle systems requires proper selection of material. The fluctuation in temperature range from lower transformation temperature to austenitizing temperature and the importance of material selection and subsequent fabrication, welding, and heat treatment assume significance. A good design increases the output and lowers the cost per unit of energy produced with minimum downtime. In this context, chrome-moly steels, especially 9Cr-1Mo steel and its later variants, have assumed significant importance in the power generation industry.

Nine chrome-moly steels have been used successfully in fossil fuel boilers. In recent years, the alloy P91 and T91in piping and tubing applications have been used in HRSGs.

Properties of 9Cr-1Mo steels' alloy that contributed to its use

- Lower thermal expansion, higher thermal conductivity
- Improved oxidation resistance compared with traditional power plant material such as American Society for Testing Materials (ASTM) A 335 Grade P-22 or A 213 Grade T-22 (2.25Cr-1Mo) ferritic steel and 300 series austenitic stainless steels

These enhanced properties, prompted designers of the power industry to use this alloy for steam-plant components. Use of this alloy allowed the choice of relatively thinner walls, thus reducing the stresses induced by thermal cycles.

Further development of these alloys with addition of niobium (Nb), vanadium (V), and nitrogen (N) significantly improved the creep-rupture strength of these alloys. This group of new alloys was later designated as "modified" 9Cr-1Mo and given new identity by ASTM as ASTM A213 Grade T91 for tubing and ASTM A 335 Grade P91 for piping, often used for headers.

It is important to point out that there is significant difference in application of tubing and piping grades. This difference is based on the following application variables:

- In piping, the metal temperature does not exceed the steam temperature because steam is the source of heat. In this condition, the thermal energy flows from the centerline of the pipe to the pipe's outside wall.
- In the superheater and reheater tubes used in the boilers, the hot furnace gas is the source of heat, and thermal energy flows from tube outside wall toward its centerline. Because of this subtle and important difference, the tube-metal temperature can be higher than the steam temperature.

Because of these different service conditions, these alloys are used for piping applications in steam service of 590°C (1100°F) and for tubing applications up to the operating steam temperature of 565°C (1050°F).

Most units of the earlier generation used alloy ASTM A 335 Grade T22 (2.25Cr/1Mo) and 304H stainless steel material for secondary superheater tubes. Several failures were reported in these tubes. As expected, the majority of these failures had creep damage as the primary mode of failure. Creep is attributed to the excessive metal temperatures. Alloy T91, which has since replaced most of these ASTM A 213-T22 and 304H tubes, now presents specific advantages in creep stress conditions. The advantages of T91 material over T22 and 304H include:

- At a given temperature, higher allowable stress can be used for design purpose.
- The T91 alloy has lower coefficient of expansion compared with stainless steels.
- T91 alloy has potential to improve plant efficiency because the turbine-inlet temperature can be raised.
- Higher allowable stress of T91 allows designers to select thinner tube walls; this reduces the possibility of thermal-fatigue cracking.

The point to be specifically addressed in the use of T91 material is its design limitations, which must be acknowledged during the design stage.

- The cost of fabrication is higher because of strict quality control and subsequent stress-reliving heat treatment.
- Procurement of quality available material from reputed steel mills.
- Control of design pressure drop through the secondary superheater with the thinner walled T91 tubes.
- Avoidance of dissimilar metal welds and very careful weld design.
- Concerns relating to the effective quality control.

Welding chrome-moly pipe requires some very specific quality control. Regardless of the grade or the welding process used for welding, maintenance of specific preheat and interpass temperatures cannot be overemphasized. This helps control slow cooling of the weld. A range of preheat temperatures from 121°C to 204°C (250°F to 400°F) can be used depending on the thickness of the material being welded. Service pipes exposed to temperatures above 450°C (850°F) for an extended period of time often exhibit temper brittleness; it is especially important to preheat these materials when repair is being attempted.

Quality assurance

Attention to quality assurance is an important factor in accomplishing a successful fabrication and subsequent service and maintenance work.

The degree of attention to quality is the key difference between the work on a fossil boiler and the combined-cycle experience with P91 and T91 material. In the fossil-boiler industry, the designers, fabricators, and installers followed all the rules. They operated with conservative design wall thickness, at reasonable steam temperatures of maximum 1050°F, and the material worked fine.

However, welding of P91 and T91 alloy requires a precise heat control during welding and subsequent PWHT, and the welds between dissimilar metals should be minimized. If it is absolutely necessary, it must be very carefully designed. This is irrespective of material thickness or diameter.

In the combined-cycle industry, modified 9Cr-1Mo is often seen as a silver-bullet remedy for two major troubles plaguing large HRSGs:

- The thermal fatigue of thick-walled components, such as main steam piping and superheater headers
- Creep damage in the superheater

Modified 9Cr-1Mo is effective because the alloy's mechanical properties allow pressure-containing components to be made of thinner sections, leading to smaller temperature gradients across the wall and reducing the time for the metal to reach thermal equilibrium, ultimately resulting in less thermal fatigue.

For example, for a typical HRSG superheater header upgrade from standard P22 to P91, a reduction in wall thickness of more than 50% and the combined weight reduction of all components by about 65% can be achieved.

In welding these modified 9Cr-1Mo alloys, the focus must be on control of the microstructure.

These are very advanced alloys, and similar to most such complex alloys, the mechanical properties depend on the creation of a precise microstructure and the maintenance of that microstructure throughout the component's service life. With traditional low-alloy steels such as Grades 11 (1.5 Cr, 0.5 Mo-Si) and 22 (2.25 Cr and 1 Mo) that operate at lower stresses (allowable stress is 15 KSI up to 800°F temperature), the microstructure produced during steel production and fabrication was of only minor importance. In fact, a wide range of microstructures were produced with a liberal approach to the heat-treatment procedures, yet they provided satisfactory service.

As stated earlier, the properties of P91/T91 depends on a precise addition of vanadium (V), niobium (Nb), and nitrogen (N) and a carefully controlled normalizing process to produce a complete phase transformation from austenite into martensite. This produces high tensile strength that has corresponding higher hardness values and, at elevated temperatures, high creep resistance. Heat treatment involves a controlled tempering process to allow V and Nb elements to precipitate as carbides and carbon nitrides. These carbides and nitrides occupy the voids (at defect sites) in the microstructure. This process of carbides and nitrides occupying the voids is called plugging or pinning. This process serves to anchor the defect sites, thereby holding the microstructure in place.

The importance of microstructure and plugging of voids with carbides and nitrides was confirmed by Onizawa's study presented in 2005 to the European Collaborative Creep Committee conference in London. A series of trial products with controlled variations of V and Nb contents were produced, and mechanical tests were conducted on these experimental alloys, both before and after a 6000-h aging process. The study confirmed that higher strength and lower ductility were entirely dependent on microstructure, which was possible only if proper precipitation of V and Nb as carbides is achieved.

Failure to achieve proper microstructure during original steel production or to maintain it during any welding, fabrication, and heat treatment will cause a phase change away from 100% properly tempered martensite or will disrupt the precipitates. Either of these effects will very adversely affect the mechanical properties of the alloy.

It may be noted, especially in case of HRSG, that any repair that is not developed along the correct heat cycle would damage the microstructure of P91/T91 material. Any localized heating or improper PWHT will result in failure of these materials.

Selection of weld consumable and postweld heat-treatment temperatures

Several welding process are used to accomplish good-quality welds; they are chosen for the ease of operation and available welding wire or electrode. The selection of welding consumables, however, has an important bearing on the end result of a good weld. Some alloying elements, such as nickel and manganese, in the consumable have a tendency to bring down the AC_1 and AC_3 and martensite start (Ms) and martensite finish (Mf) temperatures. This can result in development of untempered martensite in the weld-metal and increase the risks of intercritical heat-treating damage. The presence of less than 1% nickel in the weld-metal is often specified by welding engineers. However, the electrodes listed in SFA 5.5 Table 2 are for most of the chrome-Mo electrodes; the exception is that alloys that contain 4% or less chrome have no such limitations. This conflicts with the base metal requirements of maximum 0.4% Ni. This disconnection adds to the complications of welding and heat treatment.

Many welding procedures have been developed to address this disconnection in weld-metal and parent metal composition and its effect on the end result. Welding engineers have specified a PWHT temperature range from 732°C (1350°F) to 774°C (1425°F) if the precise chemical composition of the filler metal is not known. Alternatively, the PWHT temperature is set in the following two groups:

- For alloys that has Ni%+Mn% less than 1%, the PWHT should be 800°C (1470°F).
- For alloys that has Ni%+Mn% is between 1.5% and 2%, the PWHT should be 785°C (1450°F).

Intercritical region and tempering

The intercritical region is described as the temperature range between lower transformation temperature (AC_1) and upper transformation temperature (AC_3). One of the most significant problems with Grade 91 is postproduction exposure to temperatures within this range. When Grade 91 is exposed to this intercritical region, the martensite is partially reaustenitized, and the carbon-nitride precipitates are coarsened but do not fully dissolve back into solution. The resulting material has a part-austenite, part-martensite structure that is unable to lock in the precipitates, resulting in a substantially reduced creep-rupture strength. Such reduction in creep rupture strength promotes fine-grain cracks on the parent metal side of HAZ; this is also called type IV cracking. Such a cracking phenomenon is typically associated with P91 material. These cracks often appear in the early stages of the life and at relatively lower operating temperatures. They can subsequently grow subsurface to some distance before breaking through to the surface.

With this material's relative longer service in Europe, such cracks have been reported more from European operators than in the United States; it has no geographical reason, but the United States is heading in that direction.

Phenomena of over- and undertempering

The importance of temperature range maintenance for these materials cannot be overemphasized.

Overtempering occurs when P91 or T91 components experience prolonged exposure to a temperature below the lower critical transformation temperature (AC_1). Because of this, the martensite is not affected, but the precipitates coarsen, with a corresponding loss in creep-rupture strength.

Overtempering is a lesser risk during fabrication; however, if multiple heat treatment cycles are applied for fabrication of thick-wall components, overtempering and the resulting weakening could become a possibility.

Undertempering can also jeopardize the high-temperature properties of P91 or T91 because the required precipitation does not go to completion, and the precipitates either are absent or are of insufficient size to stabilize the structure. In addition to a loss of creep-rupture strength, risks associated with undertempering are brittle fracture and stress-corrosion cracking.

To avoid intercritical-region exposure and overtempering or undertempering, the component that is heated above 1470°F should be renormalized and tempered in its entirety, or as an alternative, the heated portion could be removed from the component for renormalizing and tempering and then replaced in the component.

Hardness testing

Another quality control at the welding and fabrication stage is the mandated testing of hardness. Because at room temperature, hardness parallels the material's room temperature tensile strength, it is a good indicator of a material's elevated-temperature behavior.

There is no specified acceptable hardness value by the American Society of Mechanical Engineers (ASME); however, if proper PWHT is carried out, the hardness value should fall within a very tight range of 200–275 HV_{10}, and this ductility will provide sufficient strength at high temperature.

Determining creep damage of in-service equipment

Because we know that creep is the function of diffusion processes, temperature and mechanical stress are contributors to creep. Creep causes permanent deformation, which can be measured as strain.

This emphasizes the importance of the method to determine the deformation caused by creep in critical areas such as the HAZ of welds. The method is applied as an online measuring tool at the operating temperature. The strain measurements obtained are the indicators of the creep rate, which can be used to calculate the actual loss of life attributable to creep and, by extension, determine the remaining life.

The method, in principle, is similar to the one used to determine the creep life of catalytic reformer tubes in petrochemical industries. The essentials of this process are to have the base data of the surface conditions ready for comparison with the image obtained later while in service. The base data are the recorded image of a rough surface, used as a baseline data (image). Two images, one recorded before and one after loading, are compared by image correlation. By analyzing the results, the strain distribution caused by the loading is calculated from relative displacements in two directions.

Fabrication and weldability of HSLA steel

Like low-alloy steels, the high-strength low-alloy (HSLA) steel is developed with very precise application of steel to address a specific segment of engineering design. One aspect of HSLA steel that is different from alloy steels is that HSLA steel is microalloyed, and they depend of that specific alloying composition to give the steel the added strength that the designers are looking for.

Because HSLA steels have microalloyed materials, its behavior (specifically the strength level for which the micro -alloying is done) can change significantly during heating associated with welding and some other fabrication processes.

This property of steel makes it especially important that a carefully considered welding procedure is developed. A case study of a similar fabrication and welding follows.

Welding high strength steels

Alloy steels, known as high-strength low-alloy (HSLA), provide increased strength-to-weight ratios over conventional low-carbon steels for only a modest price premium. Because HSLA steels are stronger, they can be used in thinner sections, making them particularly attractive for transportation equipment, components where weight reduction is important. HSLA steels are available in all standard wrought forms—sheet, strip, plate, structural shapes, bar-size shapes, and special shapes.

Typically, HSLA steels are low-carbon steels with carbon content between 0.05% and 0.25% to retain formability and weldability, and up to 1.5% manganese, strengthened by small additions of elements, such as columbium, copper, vanadium, or titanium, and sometimes by special rolling and cooling techniques. These elements are intended to alter the microstructure of carbon steels, which is usually a ferrite-perlite aggregate, to produce a very fine dispersion of alloy carbides in an almost pure ferrite matrix. This eliminates the toughness-reducing effect of a pearlitic volume fraction, yet maintains and increases the material's strength by refining the grain size, which in the case of ferrite increases yield strength by 50% for every halving of the mean grain diameter. Precipitation strength also plays a minor role.

Zirconium, calcium, and rare earth elements are added for sulfide-inclusion shape control, which increases formability. These are needed because most HSLA steels have "direction sensitive" properties.

There are two ways such steel of high strength and high toughness steels are produced:

1. By microalloying: Adding a small amount of strong carbide and nitride formers
2. By very careful control of the rolling temperature and thereby controlling rolling, in other words, thermomechanically controlled process (TMCP)

The highest strength is achieved by a combination of the two methods. The aim of both methods is to produce as small a gain size as possible; fine grain gives the best notch toughness properties.

The additional benefit is the increased weldability of the material. This is achieved by reducing the hardenability of steel; the carbon content of some steel may be as low as 0.05% with reduced presence of elements like sulfur and phosphorous.

To compensate for the loss of carbon and to increase tensile strength, a small amount of niobium (<0.10%), titanium (<0.03%), and vanadium (<0.15%) are added. In some grades of steel, strong carbide- and nitride-forming elements like molybdenum, chromium, copper, and nitrogen are also added for similar effect. These formations allow fine dispersion of stable precipitates that inhibit grain growth during the hot-rolling process and assist in nucleating fine-grained ferrite during the cooling process. Possibility of precipitation hardening is also an added advantage of these elements.

TMCP is also used for similar effect of grain refinement, leading to increased strength and toughness. TMCP is ordinarily carried out at about 850–900°C, which allows for elongated crystalline austenitic grains. Accelerated cooling from the rolling temperature develops very fine-grained ferrite on the boundaries of the austenite grains.

Improved formability of HSLA steels is achieved by addition of such elements as zirconium, calcium, or rare earth for sulfide-inclusion shape control. This is an important property to consider when designing because, due to the higher strength of the material, the parts made from HSLA steels would be relatively thinner in cross-sections compared with the parts made from low-carbon steel.

Forming and working with HSLA steel

Formability and impact strength can vary significantly when tested longitudinally and transversely to the grain. Bends that are parallel to the longitudinal grain are more likely to crack around the outer edge, because it experiences tensile loads. This directional characteristic is substantially reduced in HSLA steels that have been treated for sulfide shape control.

Grades known as "improved-formability" HSLA steels (sheet-steel grades designated ASTM A715, and plates designated ASTM A656) have yield strengths up to 80,000 psi, yet cost only about 24% more than a typical 34,000-psi plain-carbon steel. ASTM A690 is noted for corrosion resistance in seawater splash zones, so it is used in docks, seawalls, bulkheads, and related uses.

Welding HSLA steel

Despite improved weldability discussed before these steels have some fabrication challenges, one of them being HIC.

1. The low carbon content in these steels reduces the CE to as low as 0.3 or even lower. This translates into steels having very low tolerance for hydrogen cold cracking. The IIW formula for calculating CE to establish preheat is no more valid for these steels.

These steels, therefore, can be welded at significantly lower preheat temperature; this is one significant advantage over the normal carbon steel.

The highest potential for cracking of welds in these steels is not in HAZ but in the weld-metal. Some of the key reasons for this phenomenon are:

- The high strength of parent metal develops higher residual stress during welding.
- To match the tensile strength and toughness of the parent metal, the filler metal needs to be more highly alloyed and therefore will have a higher CE. Filler metal CE of up to 0.6 (IIW) is often used (for example, 700 MPa YS with E 11018 G electrode).
- The weld-metal transforms from austenite to ferrite at a lower temperature than the parent metal (a reversal of the transformation in normal carbon steel).
- As a result of the earlier point, the hydrogen in HAZ is rejected into the still-austenitic weld-metal, which has high solubility for hydrogen. A preheat based on the weld-metal composition is therefore advised, and a low-hydrogen technique must be used. The only exception to this is to allow cellulosic weld in root and hot pass in pipeline welds if a manual (SMAW) process is used, and rest of the weld has to be a low-hydrogen process. In higher grades, it is strongly recommended that proven automatic welding process with a low-hydrogen consumable be used.

2. Even though these steel contain low sulfur, the lower carbon percentage may suffer from solidification cracking in root pass, particularly if the welding speed is relatively high. This is particularly because the high dilution of filler metal produces a weld deposit that is low in carbon, which allows for excessive gain growth of austenite during welding and these large grains increase the risk of center line solidification cracking in root bead. This is a very common issue with pipeline welding that uses cellulosic electrodes; one reason for that would be the speed of deposition associated with downhand welding technique.
3. The toughness and strength in HAZ can be a serious issue, as the steel is manufactured with great control as far as TMCP process is concerned. Contrasting with that is the uncontrolled cycles of heating and cooling associated with welding. The microstructure of HAZ will vary with respect to the composition of steel and welding process heat input. A high heat input will promote gain growth, and this will have an adverse effect on both strength and toughness. As guidance only, the heat input must be controlled to about 2.5 kJ/mm or lower, and some alloys with titanium and boron can tolerate up to 4.5 kJ/mm. The interpass temperature should be maintained at 250°C maximum.

These steel are not recommended to be heat-treated after welding. PWHT may be required if thickness is in excess of 35 mm; great care is to be exercised in determining the need and process of PWHT.

ASTM A514 and A514M-05 high-strength, low-alloy, quenched-and-tempered steels are among the HSLA materials. Welding these materials successfully is a matter of understanding some key factors, including filler metal choices and preheating and interpass heat requirements.

ASTM A514 material specification has several grades (grade A, B, E, F, H, P, Q, and S). Each grade has a unique chemistry and may differ in the maximum thickness to which it is rolled, from 1–1/4 in. to 6 in. The material thickness affects the mechanical properties. For instance, A514 rolled to 2 1/2 in. or less is required to have 110,000–130,000-psi tensile strength, 100 KSI minimum yield strength and 18% elongation. For materials 2 1/2–6 in. thick, the mechanical properties are 100–130 KSI tensile strength, 90 KSI minimum yield strength, and 16% elongation.

The hardness for material thickness up to and including 3/4 in. is 235–293 HBW (Brinell). Note that the specification does not list hardness requirements for materials thicker than 3/4 in.

One of the reasons for the difference in properties among these thicknesses is the quenching. The thicker the material, the slower the quench rate, which results in lower minimum yield and tensile strengths.

Typically, this material is used for structural applications. In many cases, the term *structural* refers to buildings, but the material also is used in heavy equipment structures to reduce weight and improve payload capacity, such as in railcars and their components, large mining truck frames, semitrailer frames, and crane boom sections, etc.

Because the typical hardness of the materials is 22–27 Rockwell C, the material is also used for wear strips, cutting edges, and side cutters. Typical applications are backhoe buckets and other wear components in earthmoving equipment.

Making the Choice: Filler Metals

Welding ASTM A514 is not complicated when some precautions, especially with filler metal choices, are used.

A primary concern is filler metal hydrogen content. Filler metals that deposit weld-metal with diffusible hydrogen content greater than 8 mL/100 g of deposited weld-metal should not be used. ASTM A514 is sensitive to diffusible hydrogen, which may result in hydrogen cracking.

Typical filler metal selection

The filler metal strength depends on the application of the A514. Table 1 shows filler metals that can be used to match the strength of base materials up to 2 1/2-in. thick where the same mechanical properties as the base material are required. On base material thicknesses greater than 2 1/2 in., same filler metals can be used if the overmatching strength of weld-metal properties meets the design requirements.

Filler metal selection

When joining A514 to other low-alloy steels or carbon steels of lower strength, use a filler metal with strength that meets the lower-strength base material's properties. Keeping in mind not just the strength but keep the hydrogen-cracking risk in mind.

Heat input control

Even though A514 is readily weldable, excessive preheat and interpass temperatures and welding heat input can affect the alloy's chemical properties.

Table 3 lists typical preheat and interpass temperatures for A514. These temperatures apply whether the weld is on A514 to itself or to other, lower-strength

Table 1 ASTM A514 and A514M-05 up to 2 1/2-in. thick.

Welding process	AWS A5 specification	Classification
SMAW	A5.5/A5.5M-2005	E11018M or E12018M
GMAW	A5.28/A5.28M-2005	Solid electrodes ER 110S-1 and ER120S-1 or Metal-cored electrodes E110C-K3, E110C-K4, and E120C-K4
FCAW	A5.29/A5.29M-2005	E11XT1-K3C and -K3M E11XT5-K3C and -K3M E11XT5-K4C and -K4M E12XT5-K4C and -K4M
SAW	A5.23/A5.23M-1997	Solid electrode/flux combination F11AX-EXXX-XXX and F12AX-EXXX-XXX or composite electrode/flux combination F11AX-ECXXX-XXX and F12AX-ECXXX-XXX

Table 2 ASTM A514 and A514M-05 greater than 2 1/2-in. thick.

Welding process	AWS A5 specification	Classification
SMAW	A5.5/A5.5M-2005	E10018M
GMAW	A5.28/A5.28M-2005	Solid electrodes ER 100S-1 or Metal-cored electrodes E100C-K3
FCAW	A5.29/A5.29M-2005	FCAW A5.29/A5.29M-2005 E10XT1-K3C and -K3M E10XT5-K3C and -K3M E10XT1-K7C and -K7M E10XT1-K9C and -K9M
SAW	A5.23/A5.23M-1997	Solid electrode/flux combination F10AX-EXXX-XXX or Composite electrode/flux combination F10AX-ECXXX-XXX

materials. It should be noted that preheat and interpass temperatures higher than those shown in Table 3 may alter the mechanical properties of the material. Tempil Sticks, contact pyrometers, infrared thermometers, or other heat-measuring devices may be used to control preheat and interpass temperatures.

Table 3

Thickness (in.)	Maximum preheat and interpass temperature (°F)	Maximum preheat and interpass temperature (°F)
Up to 3/4	50	400
3/4–11/2	125	400
1 1/2–2 1/2	175	400
More than 2 1/2	225	400

In addition to the preheat and interpass temperature controls, heat input, which is a function of amperage, voltage, and travel speed, must be restricted. Heat input is expressed in joules per inch. The formula is:

$$\text{Heat Input (joules/in.)} = (\text{Amperage*Voltage*60}) \div \text{Travel Speed (IPM)}$$

Typical heat input is about 55,000 J/in. (±20%). For other heat inputs, it is advisable to contact the steel manufacturer for recommendations.

As a final precaution, ASTM A514 is not intended to be used in the postweld heat-treated (PWHT) condition, as it will alter the mechanical properties for which the material was intended. Other sources of information for welding A514/A514M-05 steel are the steel manufacturers' fabrication guides and:

AWS D1.1, Structural Code—Steel
AWS D14.3, Specification for Welding Earthmoving, Construction, and Agricultural Equipment
AWS D15.1, Railroad Welding Specification—Cars and Locomotives

Corrosion

HSLA steels are also more resistant to rust than most carbon steels due to their lack of pearlite—the fine layers of ferrite (almost pure iron)—and cementite.

Although additions of elements such as copper, silicon, nickel, chromium, and phosphorus can improve atmospheric corrosion resistance of these alloys, they also increase cost. Galvanizing, zinc-rich coatings, and other rust-preventive finishes can help protect HSLA-steel parts from corrosion.

SAE HSLA steel grade compositions

SAE grade	**% carbon (max)**	**% manganese (max)**	**% phosphorus (max)**	**% sulfur (max)**	**% silicon (max)**	**Notes**
942X	0.21	1.35	0.04	0.05	0.90	Niobium or vanadium treated
945A	0.15	1.00	0.04	0.05	0.90	
945C	0.23	1.40	0.04	0.05	0.90	
945X	0.22	1.35	0.04	0.05	0.90	Niobium or vanadium treated
950A	0.15	1.30	0.04	0.05	0.90	
950B	0.22	1.30	0.04	0.05	0.90	
950C	0.25	1.60	0.04	0.05	0.90	
950D	0.15	1.00	0.15	0.05	0.90	
950X	0.23	1.35	0.04	0.05	0.90	Niobium or vanadium treated
955X	0.25	1.35	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
960X	0.26	1.45	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
965X	0.26	1.45	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
970X	0.26	1.65	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
980X	0.26	1.65	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated

SAE HSLA steel grade mechanical properties

SAE grade	Form	Minimum yield strength (psi)	Minimum ultimate tensile strength (psi)
942X	Plates, shapes, and bars up to 4 in.	42,000	60,000
945A, C	Sheet and strip	45,000	60,000
	Plates, shapes, and bars		
	0–0.5 in.	45,000	65,000
	0.5–1.5 in.	42,000	62,000
	1.5–3 in.	40,000	62,000
945X	Sheet, strip, plates, shapes, and bars up to 1.5 in.	45,000	60,000
950A, B, C, D	Sheet and strip	50,000	70,000
	Plates, shapes, and bars		
	0–0.5 in.	50,000	70,000
	0.5–1.5 in.	45,000	67,000
	1.5–3 in.	42,000	63,000
950X	Sheet, strip, plates, shapes, and bars up to 1.5 in.	50,000	65,000
955X	Sheet, strip, plates, shapes, and bars up to 1.5 in.	55,000	70,000
960X	Sheet, strip, plates, shapes, and bars up to 1.5 in.	60,000	75,000
965X	Sheet, strip, plates, shapes, and bars up to 0.75 in.	65,000	80,000
970X	Sheet, strip, plates, shapes, and bars up to 0.75 in.	70,000	85,000
980X	Sheet, strip, and plates up to 0.375 in.	80,000	95,000

SAE ranking of various properties for HSLA steel grades

Rank	Weldability	Formability	Toughness
Worst	980X	980X	980X
	970X	970X	970X
	965X	965X	965X
	960X	960X	960X
	955X, 950C, 942X	955X	955X
	945C	950C	945C, 950C, 942X
	950B, 950X	950D	945X, 950X
	945X	950B, 950X, 942X	950D
	950D	945C, 945X	950B
	950A	950A	950A
Best	945A	945A	945A

Welding, corrosion-resistant alloys—Stainless steel

7

In the previous chapters, we have discussed the principles of welding, the types of equipment, various welding processes, and the effect of heating and cooling on material. We used some examples to stress the points of discussion; most of these examples were taken from common experiences and common material, i.e., carbon steel.

In this and subsequent chapters, we will concentrate on a specific material group, commonly known as corrosion-resistant alloys (CRAs). Stainless steel and various grades are the largest part of the CRA group. Although we have discussed various metallurgical details in Section 1 of this book, in this chapter we shall focus on these metallurgical and mechanical aspects from the welding engineer's view. While discussing these aspects, we shall apply the principles and physics of welding learned so far.

Corrosion-resistant alloys (CRAs)

The term *corrosion-resistant alloy* (CRA) is commonly used to cover all metals that are, to some degree, capable of resisting corrosion as compared with carbon steel. This resistivity to corrosion is not universal as it varies to a large degree on the specific corrosion environment and depends on the alloying composition of the given alloy.

These alloys vary considerably from each other and can be iron- or nickel-based material often alloyed with chromium or copper or any possible variations of different alloying elements. In fact, all the metals discussed in this chapter and some in subsequent chapters are part of the large and diverse family of CRA materials.

Stainless steel

Stainless steel is chosen for a project based on any single or a combination of following specific properties:

1. Resistance to corrosion
2. Resistance to oxidation at higher temperatures
3. Good mechanical properties at room temperature
4. Good mechanical properties at low temperature
5. Good mechanical properties at high temperature
6. Aesthetic values, such as good appearance

Stainless steels are corrosion-resistant materials that rely on surface passivity for resistance to corrosion attack. Use of these materials is governed by the oxidizing

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characteristics of the environment. For more oxidizing conditions, stainless steel is superior in performance to several more-noble metals and alloys, available for fabrication by welding.

Welding stainless steel

General welding characteristics

All the chromium-nickel (300 Series) austenitic stainless steels, with the exception of high-sulfur or selenium-added free-machining grade (AISI 303), are easily welded. The welded joints are tough and ductile in "as-welded" condition. These welds, if used in noncorrosive or mildly corrosive services, do not require any postweld heat treatment.

In welding, a temperature gradient is achieved ranging from room temperature to molten steel. The area that is heated in this process range from 425 °C to 900°C (800°F to 1650°F) and becomes sensitized as carbides are precipitated. This carbide precipitation may affect the life of equipment under severe corrosive conditions, therefore annealing the welded parts is recommended to restore optimum corrosion resistance. This annealing process is called *solution annealing*. The process of solution annealing consists of heating the material up to a temperature above a sensitizing temperature, generally 1100°C (or about 1960°F) and holding it long enough for the carbon to go into solution. After this, the material is quickly cooled to prevent the carbon from falling out of the solution. Solution-annealed material is in its most corrosion-resistant and ductile condition.

It is not always possible to solution anneal the weldments. This could be for various reasons such as its size or other postfabrication processes, etc. If for any reason the welded part cannot be annealed, then extreme care should be taken in welding stainless steel and either a low-carbon grade of stainless steels that have less than 0.03% carbon or AISI 321 or 347 grade of steel should be selected.

The grades 321 and 347 are stabilized alloys. They contain titanium and columbium, respectively. The ratio of these elements is dictated by the percentage of carbon in these steels, for example, the minimum amount of titanium in Grade 321 is about five times that of carbon in the steel. Similarly, columbium in Grade 347 is about 10 times that of carbon content of the steel. But accurate ratio of carbon to titanium or columbium has to be designed in the steel based on the specific requirement of the service environment including welding requirements of the project. When these steels are heated during welding and the material reaches the sensitizing range, carbide precipitation occurs, as in any other grades of stainless steel, except that due to high affinity of carbon to these elements, the carbide of titanium and columbium is precipitated, thus leaving chromium free from intergranular corrosion. In some very specialized conditions, Grade 321 may be further heat-treated by heating to 815–900°C range for 2–4 h and air-cooled to secure complete carbide precipitation as stable titanium carbides. This heat treatment is sometimes called *stress relief treatment*.

In low-carbon (less than 0.03%) grades, such as 304L and 316L, the carbon is so low that, during welding, the heat does not precipitate carbides. The use of these grades of steel is limited to service temperature below 425–870°C (800–1600°F).

Welds in other corrosion-resistant steels such as ferritic and martensitic stainless steels are not as ductile and tough as in austenitic steels discussed earlier. Ferritic alloy type 405, 430, 442, and 446 are more readily weldable. The martensitic grades like 403 and 410 are more weldable than types 420 and 440.

Welding processes

All arc-welding processes, electron beam, laser beam, resistance, and friction welding processes readily join stainless steels. Gas metal arc, gas tungsten arc, flux-cored arc, and shielded metal arc welding are commonly used. Plasma arc and submerged arc welding (SAW) are also suitable joining methods.

Restrictions on SAW are necessary because chemical composition control of the weld deposit is more difficult because of the effect of arc voltage variations. Heat input is higher, and solidification of the weld-metal is slower, which can lead to large grain size and low toughness. Ferrite contents of at least 4% are nearly inevitable. However, there are several commercial developments in the process and consumables that are able to address these concerns to some degree are now emerging in the market. More close scrutiny of the welding procedure is advised in these applications.

Oxyacetylene welding is not recommended due to the high heat input required.

Protection against oxidation

A welding process must protect the molten weld-metal from the atmosphere during arc transfer and solidification. Fluxing may be required to remove the chromium and other oxides from the surface and the molten weld-metal. Gas-shielded processes do not require fluxing as the shielding gas prevents oxidation.

Welding hygiene

Importance of cleaning before and after welding

The high chromium content of stainless steels promotes the formation of tenacious oxides that must be removed for good welding results. Surface contaminants affect stainless steel welds to a greater extent than they affect carbon steel welds.

The surfaces to be joined must be cleaned prior to welding. An area surrounding the weld joint of at least 12 mm (0.5 in.) is cleaned, a far wider area if thicker plates are being welded. As a general rule of thumb, cleaning a band of metal about 1.5 times the plate thickness will be considered good practice, as it would avoid contaminations.

Special care in surface cleaning is required for gas-shielded welding because of the absence of fluxing.

Carbon contamination can adversely affect the metallurgical characteristics and corrosion resistance of stainless steel. Pickup of carbon contaminants or embedded particles must be prevented.

Suitable solvents are used to remove hydrocarbon and other contaminants such as cutting fluids, grease, oil, waxes, and primers. Light oxide films can be removed by pickling or by carefully selected mechanical means of cleaning. Acceptable preweld cleaning techniques include:

1. Stainless steel wire brushes that are used only for stainless steels
2. Blasting with clean sand or grit
3. Machining and grinding with chloride-free cutting fluid
4. Pickling with 10%–20% nitric acid solution

Thorough postweld cleaning is required to remove welding slag. The surface discoloration is best removed by wire brushing or mechanical polishing.

Filler metals

Covered electrodes and bare solid and cored wire are available to weld most of the grades. The chemical composition of all-weld-metal deposits varies slightly from the corresponding stainless steel metal composition to insure that the weld-metal will have the desired microstructure and be free from cracks.

Covered electrodes are available with either lime or titania coverings. Lime-type covering (EXXX-15) are suitable for DCEP (electrode positive, reverse polarity) only and EXXX-16 electrodes are suitable for AC or DCEP. Type EXXX-15 electrode coverings produce deeper penetration, and Type EXXX-16 electrode coverings produce a smoother surface finish when used with DCEP current polarity system.

Covered electrodes must be stored in sealed containers or holding ovens at a temperature range of 100–125°C (200–250°F).

Austenitic stainless steels

Metallurgical concerns associated with welding austenitic stainless steels

The properties of austenitic stainless steel have value to industry, such as high ductility, excellent toughness, strength, corrosion resistance, weldability, and excellent formability and castability. Because of these properties, austenitic stainless steels are the most commonly used material from the family of stainless steels. There is a virtual continuum of austenitic alloys containing Fe, Cr, Ni, and Mo.

The distinction between highly alloyed stainless steels and lower-alloyed nickel-base alloys is somewhat arbitrary. Nickel alloys must satisfy either (a) $Cr > 19$; $Ni > 29.5$; $Mo > 2.5$, or (b) $Cr > 14.5$; $Ni > 52$; $Mo > 12$ over their entire composition range; those that do not meet this criteria, e.g., alloy 20, UNS N08020 are classified as stainless steels.

Unified Numbering System (UNS) alloy numbers starting with a prefix "S" are grouped with the austenitic stainless steels discussed in this section, whereas super-austenitic stainless steels, defined in this chapter as alloys with *F*PREN greater than 30.0 are discussed in the section entitled "Superaustenitic Stainless Steels." The alloys that begin with prefix "N" are grouped with the nickel-based alloys.

Mechanical properties of stainless steels

The lower-alloyed austenitic stainless steels, such as type 304 and 316 (UNS S30400 and S31600), possess yield strengths around 30–40 ksi (210–280 MPa) in their annealed condition. Some higher-alloyed austenitic stainless steels with nitrogen have higher yield strengths.

Cold-working often increases strength, especially in higher-alloyed austenitic stainless steels.

Cold deformation during fabrication, although less severe than that applied during temper rolling, can produce martensite in some austenitic stainless steels, thereby increasing their susceptibility to hydrogen embrittlement (HE). Fabrication processes can also induce residual stresses that may help increased prospects of stress corrosion cracking (SCC).

Many of the common austenitic stainless steels can be readily welded using matching filler metals. Higher-alloy grades are normally weldable, but nonmatching, overalloyed nickel-base filler metals are used.

Generally, these alloys are readily weldable whether for longitudinal seam-welded pipe or girth welds, etc., via a range of processes (SAW, GTAW, GMAW, SMAW, PAW, etc.). They are usually welded with matching composition filler metal. For some of the molybdenum-containing grades, overalloyed filler with an extra 1%–3% molybdenum and higher nickel content are specified. Normally, argon is used for both shielding and backing gases. Austenitic stainless steels typically require care in welding and adherence to good stainless steel welding practice.

Because these alloys are in austenitic phase, they do not have phase transformation; on cooling, they do not require preheat or postweld heat treatment (PWHT), except in some specific cases where solution annealing may be specified after welding and hot-working.

Welding technology for the typical austenitic stainless steels is common practice using standard consumables such as ER308L, etc. Welding of higher-strength (650–690 MPa UTS), 200-series austenitic stainless steels can be done with standard 308L-type fillers if matching the strength of the base metal is not critical. Use of duplex ER2209 filler metal is one way of matching or exceeding the strength of the base metal, but toughness and embrittlement concerns restrict use of this approach to service temperatures of about −40°C to 315°C (−40°F to 600°F). For cryogenic applications, such as liquefied natural gas (LNG) equipment, use of less-standard fillers such as E16-8-2 or 316L Mn, or use of nickel-base fillers such as UNS N06022, are often of selected to take advantage of necessary strength and cryogenic toughness.

Welding of austenitic stainless steels

At the beginning of this chapter, we discussed general requirements of welding and addressed fundamental essentials like sensitization control, difference in welding stainless steel and carbon steel, and importance of weld hygiene. We take those discussions further in the subsequent paragraphs.

The austenitic steels have high coefficients of thermal expansion and low thermal conductivity and are particularly susceptible to distortion during welding. They have better ductility and toughness than carbon steels and excellent notch toughness even at cryogenic temperatures. They are stronger than carbon steels above 500°C (1000°F) and have good oxidation resistance.

When austenitic stainless steels are joined to carbon steel, construction codes often mandate PWHT in the temperature range of about 550–675°C (1025–1250°F) for relief of residual stresses. These heat treatments can adversely affect intergranular corrosion and SCC resistance of the stainless steel. In these situations, use of a low-carbon grade type 304-L or stabilized grade like type 347-L is recommended. It may however be noted that the service temperature range of 304-L and 347-L is limited to −40°C to 315°C. If PWHT is one of the limiting factors imposed on the design, then other alternatives must be considered, one of them is to butter the carbon steel as described in the following.

A buttering layer of austenitic stainless steel electrode/filler wire is deposited on the carbon steel. Often, the selection is based on the available chromium in the as-deposited weld-metal, after compensating for the dilution; if the resulting weld-metal is close to the austenitic level then the buttering is completed, the most common interface electrode for welding and buttering austenitic steel and carbon steel is E 309 grade of consumable. Once the buttering is completed, the buttered carbon steel is heat-treated as required. After the PWHT is carried out to relive stresses in carbon steel, then the stainless steel member is welded onto the PWHT buttered section of carbon steel.

Heat input ranges and interpass temperatures are not especially important for the austenitic stainless steels. Interpass temperatures up to 150°C (300°F) is usually permissible.

After welding, there is usually a heat tint in the weld/heat-affected zone (HAZ) area, and it is usual to remove this in some applications where feasible. The heat tint is often removed by manual (but not mechanical) brushing, by mechanical abrasives, such as a flapper wheel, or by a suitable pickling paste or gel. The inside of small bore pipe welds, flowlines, and clad line pipe are difficult to clean, thus this requires that welding procedure uses intergas as backing to keep the inside surface oxide-free.

Weld deposit microstructures are very different from wrought metals with the same composition; 100% austenitic structure in welds is prone to cracking. Some amount of ferrite is essential to control cracking of these welds. In austenitic welds, small pools of delta ferrite often form, and carbides may also be present. The weld-metal ferrite control is essential; Schaeffler and DeLong diagrams are used to predict as-welded microstructures. These diagrams are also useful in selecting the electrode for keeping control on the ferrite in austenitic steel weld-metal.

Superaustenitic stainless steels

Material properties and applications

Like the austenitic stainless steels, the superaustenitic stainless steels are highly ductile; they have excellent toughness, high strength, outstanding corrosion resistance, good weldability, and excellent formability. The superaustenitic stainless steels are normally used where greater resistance to corrosion, especially protection from chloride pitting and crevice corrosion, is needed. Superaustenitic stainless steels are defined as austenitic, iron-based alloys that have PREN greater than 40.

The higher PREN values are achieved primarily by adding nitrogen (N) to these alloys, and upper working temperature limits of 400°C (750°F) are generally imposed by industry codes to prevent Σ (sigma) or χ (chi) phase embrittlement.

Many of the superaustenitic stainless steels, especially those containing nitrogen, possess higher yield strengths in the annealed condition than the standard austenitic stainless steels.

These alloys are generally available in most product forms (bar, wrought plate, castings, pipe, forgings, etc.) and are usually supplied in the solution-annealed condition. Specialized parts (fittings, fasteners, etc.) of these grades are not generally inventoried by stockists but rather are custom manufactured. As an alternative, suitable nickel alloys are often selected. Castings are solution annealed to homogenize the as-cast, cored, dendritic structure.

The superaustenitic stainless steels are generally used in the solution-annealed and rapid-cooled condition. Prolonged heating in the temperature range of about 510–1070°C (950–1960°F) can cause precipitation of carbides, nitrides, or intermetallic phases. This precipitation increases susceptibility to intergranular corrosion, intergranular stress corrosion cracking (IGSCC), and chloride pitting and crevice corrosion. These alloys cannot be strengthened by heat treatment.

The higher-alloy contents of the superaustenitic stainless steels give them greater resistance to the formation of martensite during cold-working. Thus, they show reduced susceptibility to HE compared with the austenitic stainless steels. The higher-alloy contents of the superaustenitic stainless steels also give them greater resistance to SCC compared with the austenitic stainless steels. Thus, fabrication-induced residual stresses are less likely to cause SCC in these alloys.

Welding and joining of superaustenitic stainless steels

These alloys are easily weldable via a range of processes such as SAW, GTAW, GMAW, SMAW, etc. All these processes have been discussed in this book. Because, in part, these alloys rely on molybdenum to provide corrosion-resistance properties, the segregation of molybdenum that occurs during solidification of welds can impair the corrosion resistance of welds. To counter this effect, the normal practice is to use overmatching composition filler metal. The overalloyed fillers typically contain about 1.5 times the molybdenum to that of the base metal. To keep these high levels of molybdenum in solid solution, nickel-based fillers are used. This ensures that even the solute-depleted dendrite cores will have local PREN values meeting or exceeding the PREN of the base metal. Examples of such filler metals include UNS N06625, N06022, and N06686 wires.

From the earlier description of weldability of these molybdenum-alloyed steels, autogenous welding is not normally recommended for superaustenitic stainless steels, although it has been performed successfully in thin sections of <2 mm and with special gases. Some specialized postweld solution annealing can also restore autogenous welds to corrosion-resistance levels approaching that of the base metal. Normally, argon is used for shielding gas, but the addition of small amounts of nitrogen is considered more beneficial. Backing gases can be argon or nitrogen. As with high-alloy stainless steels, care is typically taken in welding superaustenitic, and adherence to good stainless steel welding practice is generally considered to be good practice. Suitable joint design, interpass temperatures, and low heat inputs is the path to successful welding of these alloys. Pre- and postweld heat treatment are not required for superaustenitic stainless steels.

During welding, heat input ranges and interpass temperatures are very carefully monitored and controlled. The maximum permissible heat input and interpass temperature increase with section thickness. The values for these parameters generally decrease as the alloy content increases. Specialist publications for suitable values for a specific joint should be consulted. If heat input or interpass temperatures are kept too high, the risk of precipitating sigma or chi phases in the HAZ or weld-metal increases. These intermetallic phases are rich in chromium and molybdenum, thus leaving a chromium-depleted area around them, which is responsible for reducing the localized corrosion resistance in these metals (Figures 2-7-1 and 2-7-2).

The austenite stainless steels contain a combined total chromium, nickel, and manganese content of 24% or more, with the chrome generally above 16%. Nickel and manganese stabilize austenite to below room temperature.

Ferrite content is designated by a ferrite number (FN). Ferrite is difficult to measure accurately, although automated equipment is now available. The importance of ferrite in weld microstructure cannot be understated, as it increases resistance to hot-cracking. Ferrite provides sites with good ductility for interstitial or tramp elements to distribute. However, excessive ferrite can also lower corrosion resistance and high temperature properties of material.

Welding parameters and technique have a significant effect on the amount of ferrite formed and retained in a weld, and they must be controlled to reduce desired properties in the weld.

Difficulties associated with welding stainless steel

Austenitic stainless steel welding appears to be similar to normal carbon steel welding. But little more in-depth observation will reveal that it is anything but similar to carbon steel welding. This is basically due to the metallurgical difference between the two types of steel; stainless steel does not undergo the normal phase changes associated with carbon steels. Whereas ferritic steels are austenitic and nonmagnetic, and at

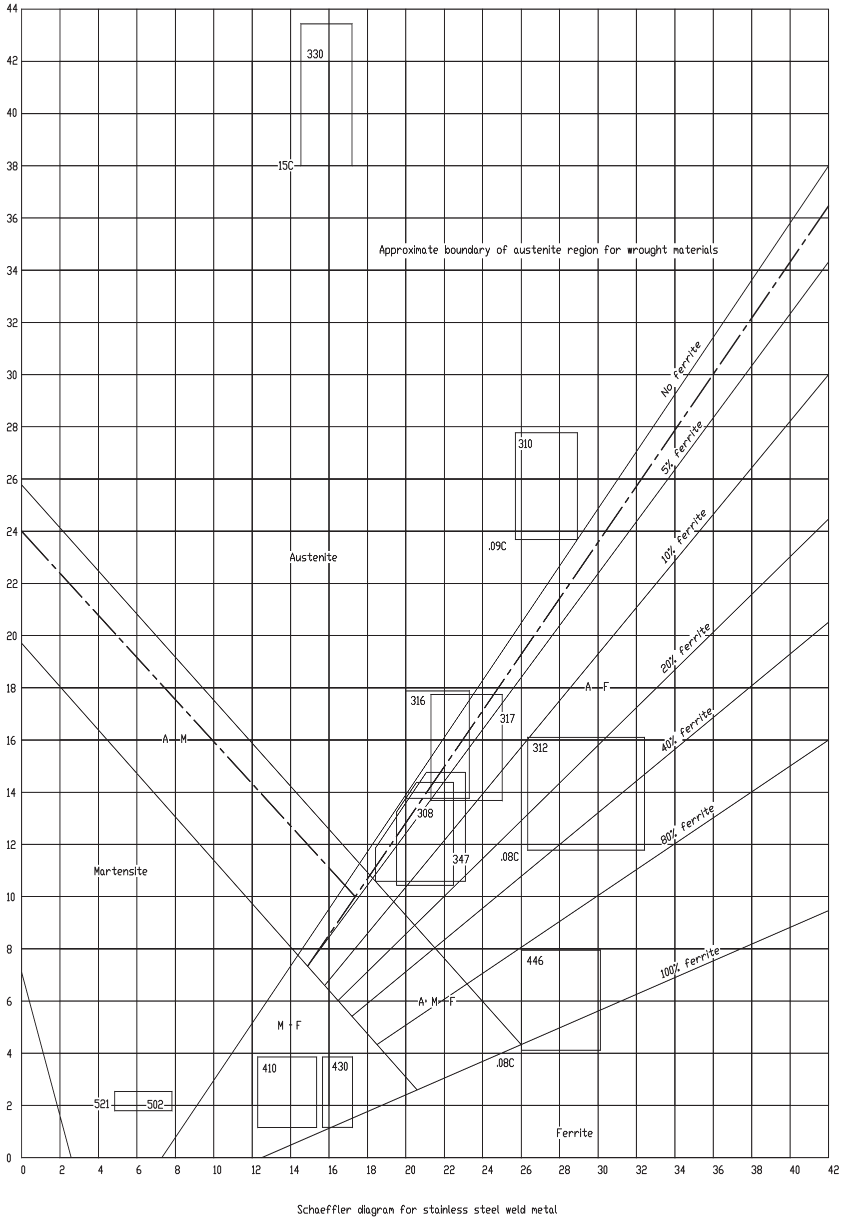

Figure 2-7-1 Schaeffler diagram.

elevated temperatures they transform to ferrite, pearlite, martensite, and other phases as they are cooled through the transformation range.

In contrast, when stainless steel is cooled, all or nearly all of the material retains the austenite structure at room temperature. No phase changes occur, and no hardness

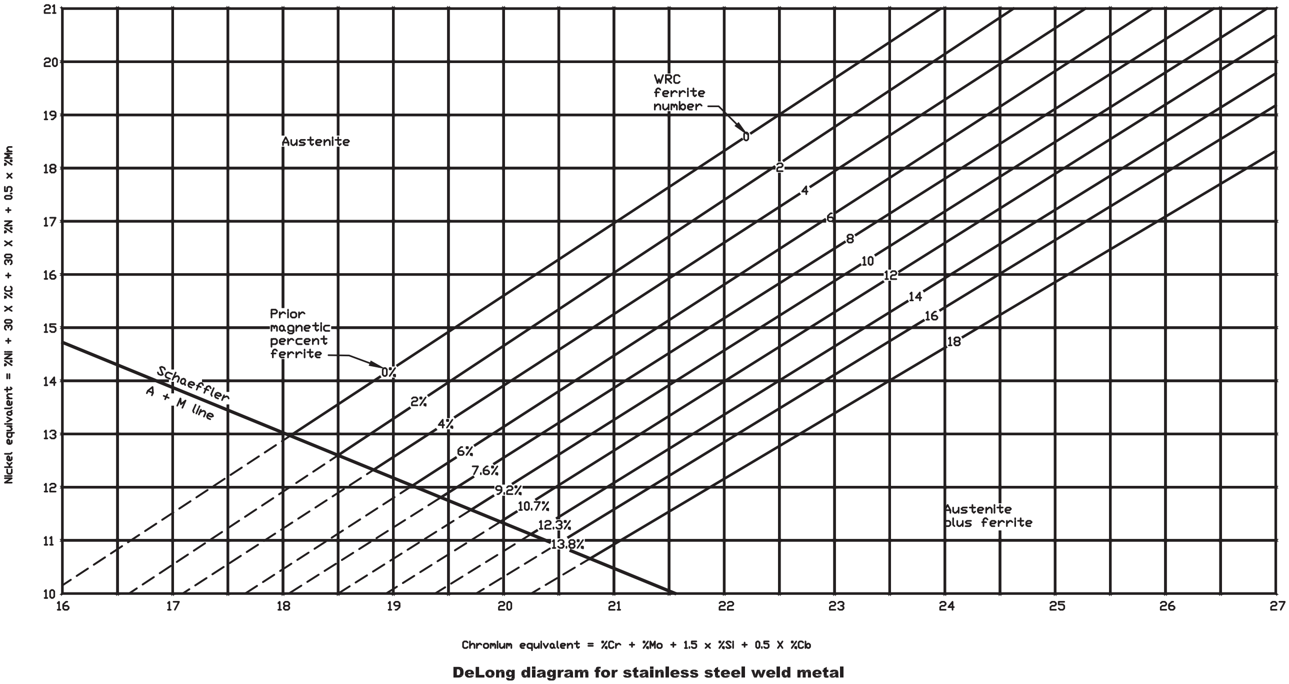

Figure 2-7-2 DeLong diagram.

increase is associated with cooling. This property of austenitic steels reduces the need to preheat or postheat.

When these steels are welded, two very specific points need to be considered.

1. Carbide precipitation or sensitization
2. Microfissuring, ferrite content, and sigma phase formation

The corrosion resistance of austenitic steels depends on the addition of various alloys of which chromium is of primary importance.

In our earlier discussion on stainless steel welding, we introduced terms like sensitization, sigma phase, etc.; here, we discuss them in little more detail. When austenitic steel is heated to a temperature range called "sensitization range," that is 425–870° C (800–1600°F), some of the chromium in the solution can combine with any carbon that is available and form a chromium-rich precipitate called chromium carbide, thus reducing the chromium in the steel. Now less chromium is available in the alloy to carry its primary duty, which is to resist corrosion. This reduction of chromium by forming chromium carbide is called sensitization.

The steel in such venerable conditions is easily attacked by an acidic environment. Under certain conditions, austenitic welds are subject to intergranular corrosion. A narrow band of metal in the HAZ is always heated to the sensitizing range. The amount of precipitation that occurs is a function of the carbon content. Carbon levels higher than 0.03% are particularly susceptible.

Many metallurgical solutions are available to overcome the formation of a sensitized area in austenitic welds; we discuss them in subsequent paragraphs.

As we have discussed the importance of austenite in steel for corrosion resistance, we may make it clear that although pure austenite has excellent mechanical and corrosion-resistance properties, its ability to absorb impurities without cracking during solidification is severely limited. During the cooling process, the low meting impurities are forced out to the grain boundaries. Excessive amounts of such grain boundary accumulations weaken the material at the grain boundary. They create grain boundary flaws called "microfissures." This condition is of significance in welding because, in relation to the parent metal, a very small area is associated with welding. One method to reduce such microfissuring is to disperse these impurities among the disconnected grain boundaries that surround the island of second phase. This can be accomplished by modifying the chemical composition of steel that would allow creation of islands of ferrite in the welds. Ferrite has enormous capacity to absorb impurities, and ferrite islands are dispersed throughout the microstructure. The presence of ferrite has the potential to very slightly reduce the corrosion resistance of steel; however, it can certainly prevent microfissuring, which is more serious and can lead to catastrophic failures. On the other hand, too much ferrite is also detrimental to the material. It can cause other problems called a "sigma phase" developed within the welding temperature range. This is a very brittle constituent and is caused by very evenly dispersed ferrite; even a small amount of sigma phase will embrittle large areas of stainless steel.

It is clear that both minimum and maximum limitations on ferrite phase are desirable in stainless steel welding to prevent microfissuring and sigma phase embrittlement.

Because carbon rapidly decreases the corrosion resistance and changes the properties of austenitic welds, it must be carefully controlled. Filler metals are usually chosen to match the base metal composition.

It is established that the ferrite content must be appropriate for the weldment's service requirements. Many electrodes are developed to produce deposits containing ferrite limits within the range of 4–10 FN. There are methods that can measure ferrite in the weld; one of them is magnetic ferrite gauge as described in AWS A 4.2.

Martensitic stainless steels

Properties and application

Martensitic stainless steels are Fe-Cr-C alloys capable of the austenite-martensite transformation under all cooling conditions. Compositions for most of martensitic steel alloys are covered by a number of specifications, such as ASTM A 420 or API 13 Cr L80 and 420 M with additional small amounts of Ni and/or Mo. Although 9Cr-1Mo is not strictly a martensitic stainless steel, it is often included in this alloy group, especially because of challenges associated with welding of 9-Cr-Mo steel is, in many ways, similar to this group of materials.

The martensitic stainless steels are generally used in the quenched and tempered, or normalized and tempered condition. For services where hydrogen evolution or presence of sulfur is expected, as in sour gas services in oil and gas industry, a maximum hardness of 22 HRC is specified by most of the specifications and for most of the alloys. Some of the alloys like type 410 and 420 develop quench crack if quenched in water, so they are quenched only in oil or polymer, or air-cooled before tempering.

Some alloys like type 410, type 415, and J91540 (CA6NM) receive a second temper treatment called "double tempering" at a temperature lower than the first tempering temperature, to reduce the untempered martensite in type 410, type 415, and J91540 (CA6NM). Double tempering has not been shown to improve resistance to SCC in type 420 tubular products and for 9Cr-1Mo tubular or forgings.

The mechanical properties of typical base metal strength (SMYS) is grouped as 414 MPa (60 ksi), 517 MPa (75 ksi), 552 MPa (80 ksi), and 586 MPa (85 ksi), with hardness controlled to the maximum 22 or 23 HRC, and often have specified to maximum yield strength of 95–100 ksi (660–690 MPa). For sour service applications, the tubular products are generally used according to the API Specification 5CT, or L-80, strength level; forgings and castings are generally specified with hardness not exceeding 22 on Rockwell C scale. Higher strengths are used in sweet service; however, corrosion resistance and ductility are adversely affected as the strength of steel is increased.

Welding martensitic stainless steels

Weld design strength levels range from 414 MPa (60 ksi) upward, but they can be different than the parent metal; for example, a 552 MPa (80 ksi) mandrel could be welded with a duplex or austenitic stainless filler metal that results in a lower weld joint strength, provided this has been considered to meet the design and operation demands.

The martensitic stainless steels are easy to work with, including welding; the welding processes used include SMAW, GMAW (MIG/MAG), FCAW, GTAW (TIG), SAW, EBW, and laser beam welding (LBW). Typical welding consumables include 410 Ni Mo (matching weld-metal), or 2209, 309LSi (overmatching consumables), whereas some limited application of autogenous welding is also practiced. These alloys are not used in the as-welded condition in more demanding environments such as sour service.

Extreme care is typically required when these alloys are welded, because they are susceptible to high hardness. Tubing and casing are generally not welded.

When welding type 410, high preheat temperatures are used. The alloys classified as type 410, type 415 (F6NM), and J91540 (CA6NM) are tempered again as a postweld heat treatment after welding to ensure that they have maximum specified strength and hardness. These alloys have been welded using nominally matching filler metals. The use of nonmatching austenitic-type consumables can increase the risk of fusion boundary cracking in sour service; this increase in fusion boundary cracking is irrespective of the hardness limits in the weld area.

These alloys are known for moderate corrosion resistance, heat resistance up to 535°C (1000°F), relatively low cost, and the ability to develop a wide range of properties by heat treatment.

If left in an as-welded condition, intergranular (sensitization) cracking is a common occurrence in both sweet (CO_2 containing) and sour conditions. These problems also arise as a result of poor PWHT cycles, where the treatment has been ineffective in refining structure and reducing HAZ hardness.

They are capable of air-hardening from temperatures above 815°C (1500°F) for nearly all section thicknesses. Maximum hardness is achieved by quenching from above 950°C (1750°F). They lack toughness in the as-hardened condition and are usually tempered.

Martensitic alloys can be welded in any heat-treated condition. Hardened materials will lose strength in the portion of the HAZ. With a carbon content of 0.08% and 12% Cr (Type 410), the HAZ will have a fully martensitic structure after welding. The steep thermal gradients and low thermal conductivity combined with volumetric changes during phase transformation can cause cold-cracking.

The hardness of the HAZ depends primarily on the carbon content and can be controlled to some degree by developing an effective welding procedure. As the hardness of the HAZ increases, its susceptibility to cold-cracking becomes greater and its toughness decreases.

Weldability is improved when austenitic stainless steel filler is used because it will have low yield strength and good ductility. This also minimizes the strain imposed on the HAZ.

Martensitic steels are subject to hydrogen-induced cracking like low-alloy steels. Covered electrodes used for welding must be low-hydrogen and maintained in dry condition.

Preheating and good interpass temperature control are the best means to avoid cracking. Preheating is normally done in the 200–315°C (400–600°F) range. Carbon content, joint thickness, filler metal, welding process, and degree of restraint are all factors in determining the preheat, heat input, and postweld heat treatment requirements.

Postweld heat treatment is performed to temper or anneal the weld-metal and HAZ with the aim to decrease hardness and improve toughness, and to decrease the residual stresses associated with welding. Subcritical annealing and annealing is performed. When matching filler metal is used, the weldments can be quench-hardened and tempered to produce uniform mechanical properties.

Types 416 and 416Se are free-machining grades that must be welded with caution to minimize hydrogen pickup. ER312 austenitic filler metal is recommended for welding type 416 and 416Se alloys, as it can tolerate the sulfur and selenium additions.

Type 431 stainless can have high enough carbon to cause HAZ cracking if proper preheat, preheat maintenance, and slow cooling procedures are not followed.

Ferritic stainless steels

Properties and application

Ferritic stainless steels are Fe-Cr-C alloys with ferrite stabilizers such as aluminum (Al), columbium (Cb), molybdenum (Mo), and titanium (Ti) to inhibit the formation of austenite on heating. Therefore, they are nonhardenable. In annealed conditions, lower-alloy ferritic stainless steels have mechanical properties somewhat similar to the low-alloy austenitic stainless steels like type 304. The typical yield strength is in the range of 30–50 ksi (205–345 MPa). Alloys with increased chromium, molybdenum, and nickel content have higher strengths.

In the high-chromium-containing alloys such as UNS S44626, the welding procedure typically developed to minimize interstitial pickup during welding and to retain material toughness. These alloys are predominantly utilized as thin-walled tubing products.

These alloys generally exhibit a loss of toughness with increasing section thickness, and a maximum thickness has been established for each alloy depending on the toughness requirements. In high-chromium-containing alloys, the interstitial contents have been carefully controlled for this purpose.

First-generation ferritic alloys (Types 430, 422, 446) are subject to intergranular corrosion after welding and exhibit low toughness.

Second-generation ferritic alloys (Types 405 and 409) are lower in chromium and carbon, and have powerful ferrite formers and carbide formers to reduce the amount of carbon in solid solution. Although they are largely ferritic, some martensite can form as a result of welding or heat treating. Ferritic alloys are low cost and have useful corrosion resistance with low toughness properties.

Recent improvements in melting practice have resulted in third-generation ferritic alloys with very low carbon and addition of nitrogen, e.g., Types 444 and 26-1 steel. Stabilizing with powerful carbide formers reduces their susceptibility to intergranular cracking after welding, improves toughness, and reduces susceptibility to pitting corrosion in chloride environments and to SCC.

The most important metallurgical characteristic of the ferritic alloy is the presence of enough chromium and other stabilizers to effectively prevent the formation of austenite at elevated temperature. Most grades do form some small amount of austenite as interstitials are present.

Because austenite does not form and the ferrite is stable at all temperatures up to melting, these steels cannot be hardened by quenching. The small amounts of austenite that may be present transform to martensite and are easily accommodated by the soft ferrite.

Annealing treatment at 760–815°C (1400–1500°F) is required to restore optimum corrosion resistance after welding. Ferritic stainless steels cannot be strengthened appreciably by heat treatment. These steels are generally used in the annealed condition. The cooling rate from the annealing temperature chosen depends on the particular alloy. The importance of proper heat treatment is emphasized by the fact that the higher-chromium-containing alloys are subject to embrittlement by sigma or alpha prime phase if not properly heat-treated.

All ferrites, if heated above 927°C (1700°F), are susceptible to severe grain growth; due to this, the material toughness is reduced, and it can only be restored by cold-working and annealing.

Welding ferritic steel

Types 430, 434, 442, and 446 are susceptible to cold-cracking when welds are made under heavy restraint. A 150°C (300°F) preheat can minimize residual stresses that contribute to cracking. These steel grades are also susceptible to intergranular corrosion.

Filler material selection would include any of the three available options.

(1) Matching compositions
(2) Use of austenitic stainless steels consumables
(3) Use of nickel alloy consumables

Matching fillers are normally used only for Types 409 and 430. Austenitic stainless steels electrode or filler wire matching E 309 or E312 grade or nickel alloys are often selected for dissimilar welds.

The need for preheating is determined by the chemical composition, desired mechanical properties, thickness, and conditions of restraint. High temperatures can cause excessive grain growth, and HAZ cracking can occur in some grades. Low 150°C (300°F) and interpass temperatures are usually recommended.

If postweld heat treatment is deemed necessary, it is done in the 700°C (1300°F) to 843°C (1550°F) range to prevent excessive grain growth. Rapid cooling through the 538°C (1000°F) to 371°C (700°F) range is necessary to prevent embrittlement.

Precipitation hardening stainless steels

Properties and application of precipitation hardening steels

Precipitation hardening (PH) stainless steels can develop high strength with simple heat treatments. They have good corrosion and oxidation resistance without the loss of toughness and ductility normally associated with high-strength materials. PH is promoted by alloying elements such as copper (Cu), titanium (Ti), columbium (Cb), and aluminum (Al). Submicroscopic precipitates formed during the aging treatment increase hardness and strength.

Martensitic PH steels provide a martensitic structure that is then aged for additional strength. Semiaustenitic precipitation hardened steels are reheated to form martensite and also aged. Austenitic PH steels remain austenitic after cooling, and strength is obtained by the aging treatment.

As a group, the PH steels have corrosion resistance comparable to the more common austenitic stainless steels. Corrosion resistance is dependent on the heat treatment and the resulting microstructure. Welding can reduce corrosion resistance by overaging and sensitization.

PH steels tend to become embrittled after exposure to temperatures above 300°C (580°F), particularly if heated for long periods of time in the range of 370–427°C (700–800°F) temperature. After welding, the maximum mechanical and corrosion resistance properties can be obtained by solution heat treatment followed by aging. For some applications, only aging treatment is sufficient.

Martensite PH steels are often fabricated in the annealed or overaged condition to minimize restraint cracking. Solution heat treatment and aging is performed after fabrication.

Welding precipitation hardened (PH) steels

Semiaustenitic PH steels are welded in all conditions. Austenitic conditioning and aging is performed after welding for maximum mechanical properties. Austenitic PH steels are difficult to weld because of cracking problems. Matching, nickel alloy, or austenitic filler materials are used. The selection of suitable filler metal is dependent on the postweld heat treatment and final property requirements.

The following are the key points that must be kept in mind for selection of material as well as welding of all stainless steels discussed thus far.

- Thermal expansion, thermal conductivity, and electrical resistivity have significant effects on the weldability of stainless steels.
- The relatively high coefficient of thermal expansion and low thermal conductivity of austenitic stainless steel require better control of distortion during welding.
- Low thermal conductivity for all stainless steels indicate that less heat input is required.
- The weldability of the martensitic stainless steels is affected mainly by hardenability that can lead to cold-cracking.
- Welded joints in ferritic stainless steels have low ductility as a result of grain coarsening related to the absence of an allotropic transformation.
- The weldability of the austenitic stainless steels is governed by their susceptibility to hot-cracking.
- The PH stainless steels have welding difficulties associated with transformation (hardening) reactions.
- Stainless steels that contain aluminum or titanium can only be welded with gas-shielded processes.
- Joint properties of stainless steel weldments will vary considerably as a result of their dependence on welding process and technique variables.
- Suitability for service conditions such as elevated temperature, pressure, creep, impact, and corrosion resistance must be carefully evaluated. The complex metallurgy of stainless steels must be accounted for (Table 2-7-1).

Table 2-7-1 Summary of the heat treatment and electrode selection for welding.

AISI type	Recommended heat treatment		Common recommended electrode for welding
	Preweld	**Postweld**	
301, 302	Not required if steel temp is above 15°C	Rapid cooling from temperatures between 1065°C and 1150°C (1950°F and 2100°F), if service condition is moderate to severe corrosive.	308
304	As above	Rapid cooling from temperatures between 1010°C and 1095°C (1850°F and 2000°F), if service condition is severe corrosive.	308
304L	As above	Not required for corrosion resistance.	308L, or 347
309, 310	As above	Not required for corrosion resistance, because steel is usually at higher temperature in service.	309, 310
316	As above	Rapid cooling from temperatures between 1065°C and 1150°C (1950°F and 2100°F), if service condition is severe corrosive.	316
316L	As above	Not required for corrosion resistance.	316L
317	As above	Rapid cooling from temperatures between 1065°C and 1150°C (1950°F and 2100°F), if service condition is severe corrosive.	317
317L	As above	Not required for corrosion resistance.	317L
321,347	As above	Not required for corrosion resistance.	347
Ferritic and martensitic steels			
403,405	150–300°F Light gauge sheet needs no preheat	Air cool from 1200°F/1400°F (650°C/760°C).	410
410	As above	Air cool from 1200°F/1400°F (650°C/760°C).	410
430	As above	Air cool from 1400°F/1450°F (760°C/785°C).	430; can be welded with 308, 309, or 310 without preheat.
442	As above	Air cool from 1450°F/1550°F (785°C/840°C).	446
446	300–500°F	Rapid cooling from temperatures between 840°C and 900°C (1550°F and 1650°F).	446
501	300–500°F	Air cool from 1325°F/1375°F (715°C/745°C).	502
502	300–500°F Light gauge sheet needs no preheat	Air cool from 1325°F/1375°F (715°C/745°C).	502; can be welded with 308, 309, or 310 without preheat.

Duplex stainless steels

This alloy group was developed over the past 30 years; the development progress has resulted in a range of compositions including lean 22% chromium (Cr) and 25% chromium, listed in Table 2-7-2. These alloys have high strength, good toughness, good corrosion resistance, good weldability, and formability, all of which ease manufacturing. These alloys combine the strength characteristics of ferritic stainless steels and the corrosion resistance of austenitic stainless steels. They have higher resistance to environmental corrosion than austenitic stainless steels. Dual-phase alloying requires relatively lower Ni and Mo content than single-phase austenitic alloys.

The alloys with higher F_{PREN} values are possible as a result of adding nitrogen to the alloy.

The key property of the duplex stainless steel contain up to 22% chromium is that it is of value to industry due to the material's pitting resistance F_{PREN}, which is typically in the range of 35–40.

The chromium content of super duplex steel is up to 25%, and its pitting resistance F_{PREN} is typically in the range of 40–45.

Mechanical properties

The mechanical properties of the different types of duplex stainless steel are shown in Table 2-7-3. The mechanical properties of the cast versions of these alloys (e.g., UNS J93380, J92205, etc.) are lower than their wrought counterparts. ASTM A 995 "Standard Specification for Castings, Austenitic-Ferritic (Duplex) Stainless Steel, for Pressure-Containing Parts" details the compositions and mechanical properties of cast duplex alloys used for pressure-containing parts.

The duplex stainless steels used by the oil and gas industry have a roughly 50/50 austenite/ferrite; in general, the duplex steel of various types would present a phase

Table 2-7-2 Nominal compositions of some of duplex steels.

Type	**UNS No.**	**Nominal composition (wt%)**							F_{PREN}
		Fe	**Cr**	**Ni**	**Mo**	**N**	**Cu**	**W**	
Lean	S32101	Bal	21	1.5	0.5	0.16	0.5	–	25
	S32304	Bal	23	4	0.3	0.16	0.3	–	26
	S32003	Bal	20	3	1.7	0.16	–		>30
Standard	S31803	Bal	22	5	3	0.16	–	–	35
	S32205	Bal	22	5	3.2	0.16	–	–	35
25 Cr	S32550	Bal	25	6	3	0.2	2	–	37
Superduplex	S32750	Bal	25	7	3.5	0.27	0.2	–	>40
	S32760	Bal	25	7	3.5	0.25	0.7	0.7	>40
	S32520	Bal	25	7	3.5	0.25	1.5	–	>40
	S39274	Bal	25	7	3	0.26	0.5	2	>40

Table 2-7-3 Mechanical properties of the different types of duplex stainless steel.

Type	0.2% proof stress (MPa)	Tensile strength (MPa)	Elongation (%)
Lean duplex	450	620	25
Standard duplex	450	620	25
25 Cr duplex	550	760	15
Superduplex	550	750	25

balance within the range 35%–65% ferrite. They have adequate toughness at low temperatures, and the alloy is commonly used to temperatures as low as −60°C (−76°F).

Superduplex stainless steel (UNS S32760) has been successfully used up to −120°C (−184°F), but this requires a well-developed welding procedures and closely monitored welding parameters during the production process.

On long exposure to temperatures above 320°C (608°F) and up to about 550°C (1022°F), the ferrite decomposes to precipitate alpha prime. This phase causes a significant loss of ductility; hence, duplex stainless steels are not normally used above 300°C (572°F).

In oil and gas service applications, these alloys have fared very well in both sour and sweet environmental conditions.

Heat treatment

Generally, these alloys are used in the annealed or annealed and cold-worked condition. Prolonged heating at temperatures between 260°C and 925°C (500°F and 1700°F) can cause the precipitation of a number of phases, including sigma, which reduces toughness and can reduce SCC resistance. Any prolonged heating below the minimum solution-heating temperature is to be normally avoided. Low-temperature toughness generally decreases with decreasing cooling rates in annealing.

Welding and fabrication

Cold-worked alloys are usually not welded because the mechanical strength of the weld would be lower than the base metal. Annealed alloys are easily welded. The weld filler metal is chosen to produce a desired volume fraction of ferrite and austenite. Hence, fabrication using autogenous (without filler) metal can result in welds that are poorer in mechanical and corrosion-resistant properties. The welding procedure is typically developed to control and balance the ferrite/austenite phase, and this is essential to prevent deleterious phases or intermetallics.

These alloys are readily weldable by SMAW, SAW, GTAW, or GMAW processes. Other processes are also successfully used. Where the weld is to be heat-treated after completion, it is usual practice to weld with matching composition filler metal.

In an as-welded application, it is normal to use an overalloyed filler metal with an extra 2%–2.5% nickel (Ni). This helps in getting the austenite/ferrite phase balance of about 50/50, if the weld is cooled rapidly. The lean duplex grades are welded with the filler metal used for 22% Cr duplex stainless steels. Except for thin sheets of up to 2 mm thickness, autogenous welding is normally not recommended for duplex stainless steels.

Normally, argon gas is used for both shielding and backing gases, and welding does not begin until the oxygen level is dropped below 0.1%. As with high-alloy stainless steels, care is to be taken in welding duplex alloys, and adherence to good stainless steel welding practice discussed earlier in this chapter is a good practice. Good joint design, control of interpass temperatures, and keeping low heat inputs are other essential variables for good welding. Preheat and postweld heat treatments are not required for duplex stainless steels.

Maximum permissible heat input and interpass temperature increase with section thickness. The values for these parameters generally decrease as the alloy content increases. If heat inputs or interpass temperatures are too high, there is a risk of precipitating sigma (Σ) or chi (χ) phases in the HAZ or weld-metal. These are intermetallic phases, rich in chromium and molybdenum that leave a denuded area around them, which reduces the localized corrosion resistance. Sigma (Σ) and chi (χ) phases also reduce impact toughness properties. In many applications, especially in some oil and gas applications, the low temperature toughness is compromised for the corrosion-resistance properties.

After welding, there is usually a heat tint in the weld and HAZ, and it is normal to remove this by manual brushing, mechanical abrasives, or suitable pickling solutions or gels.

While developing welding procedures, it is common and advised to include a corrosion test, for example, testing according to ASTM G 48 (http://www.astm.org/) as part of the weld qualification procedure.

The corrosion test sets important weld parameters; hence, it is essential that the qualified parameters of welding are followed very closely during production welding. The experience tells us that sometimes “less experienced” welders have difficulty passing the corrosion test. Although the weld made by these less experienced welders would meet the mechanical requirements, it may not meet the corrosion tests as specified. This increases the importance of welders/operators qualification test and production weld parameters monitored by inspectors. In a very limited way, this problem is resolved with use of 2% nitrogen gas along with argon as a shielding gas. The reasons for the corrosion test failure can be due to the development of third phases, which are the result of poor supervision and control over the heat input and the interpass temperature.

Duplex stainless steel welds usually have lower impact toughness than their parent metals. The welding process used often affects the level of toughness, the GTAW welds being the toughest and SAW being the poorest. The weld-metal toughness is a function of both the heat input and the type of flux used. The experience suggests that a minimum of 70-J Charpy impact toughness in the parent metal ensures adequate toughness in a duplex weld, and it is easily achieved when correctly welded. To improve the low temperatures toughness requirements, especially for very low temperature services, it is worth considering the use of nickel alloy filler metals, taking into account that other properties are not compromised, for example, the nickel alloy weld must have the same strength as the parent duplex stainless steel. A practical example of this would be the selection of C-276 (UNS N10276) filler metal to improve the impact toughness of cast superduplex (UNS J93380) at −120°C (−184°F) service.

Some specifications for duplex material that are used in subsea environments with cathodic protection (CP) require maximum austenite spacing. In a weld, this cannot be controlled, and the result cannot be changed by any heat treatment. However, duplex welds usually have a fine microstructure, and meeting a maximum austenite spacing of 30 μm is usually not difficult. Although the welding in itself does not necessarily degrade the resistance of duplex stainless steel against HISC, the presence of higher stress and stress raisers, such as weld toe, poses a significant problem when uncoated duplex stainless steels or steels with defective coating are exposed to CP under mechanical stress. Failures have occurred as a result of this effect, and guidance to avoid them can be sought from industrial specifications.

Welding nonferrous metals and alloys

8

Nonferrous metals and alloys occupy important positions among engineering construction materials. A large part of fabrication is done where nonferrous material and alloys are used for their specific properties. A large number of materials are developed to meet specific properties. It is not practically possible to discuss all of them; however, some of the more common materials are discussed in this chapter.

The knowledge of these metals and alloys will build a foundation on which the understanding of the rest of the materials can be built, and new challenges can be faced with some degree of confidence.

Aluminum and alloys

Aluminum is an element and metal like iron, but in many ways it is different from iron, and its most important alloy is steel. For example, aluminum has only one allotropic form, so there are no phase transformations, and this property can be exploited to control its microstructure. The main methods by which aluminum can be strengthened include deformation, solution hardening, or by introducing precipitates into the microstructure. From welding engineer's view, it is a very useful material; it is easily weldable and relatively easily formed into useful shapes and sizes. The heat introduced by welding can severely disrupt the deformed or precipitation-hardened alloys.

Aluminum forms a tenacious oxide film; it is impossible in practice to stop it from oxidizing at exposed surfaces. For a welding engineer, it is a challenge to find a way to remove this oxide film and prevent its formation and reformation during welding. However, it can be welded by dispersing the adhering oxide by the action of chemicals, or a welding arc, although fragments of oxide are often entrapped into the weld if a special welding environment is not created. For example, resistance spot welding of aluminum is difficult (although not impossible) because the oxide film can cause uncontrolled variations in surface resistance.

There have been quite remarkable developments in the joining of aluminum and its alloys. A few of these achievements are reviewed, including friction-stir welding, flux-free brazing, transient liquid-phase bonding using a temperature gradient, and the joining of aluminum forms.

Confusing things about aluminum

There are a few characteristics of aluminum metal that must be considered if this material is to be welded with consistent ease and quality. The pure aluminum metal has a melting point less than 650°C (1200°F), and unlike steel, aluminum does not

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exhibit color changes before melting. For this reason, aluminum does not "tell you" when it is hot and ready to melt. The oxide or "skin" that forms so rapidly on its surface has a melting point almost three times that of the pure aluminum, over 1760°C (3200°F). To add to this confusion, aluminum boils at about 1582°C (2880°F), which is a temperature less than the melting temperature of oxide adhering on the surface. The oxide is also heavier than aluminum; as a result, when the oxides are melted, they tend to sink in the molten metal and be trapped. Due to these complex reasons, it is recommended that the oxide film must be removed from the surface before starting to weld.

Weld hygiene

The practice of good weld hygiene for any metal is important, but for welding aluminum, it can never be overemphasized.

To weld aluminum, operators must take care to clean the base material and remove any dirt, aluminum oxide, and hydrocarbon contamination from oils or cutting solvents left over from previous processes like machining, etc. As stated earlier, there is a significant difference in the melting temperature of the oxide films on aluminum surface and the melting temperature of aluminum itself. This emphasizes the need for removing the oxide prior to commencement of welding.

Stainless-steel bristle wire brush or solvents and etching solutions are commonly used to remove aluminum oxides. There is special technique of brushing to prevent entrapment of particles of removed oxides in the "cleaned" surface. The direction of the brush movement must be in one direction; no crisscross brushing or reverse brushing should be done. Care must be taken to brush lightly; too rough brushing is likely to further imbed the oxide particles into the work-piece. Cross-contamination with other material should be avoided.

If chemical etching solutions are used, it is important to make sure that the remnants of the chemical is fully removed from the work before application of welding heat.

To minimize the risk of hydrocarbons from oils or cutting solvents entering the weld, they are to be removed with a degreaser. Ensure that the degreaser used does not contain any hydrocarbons to further contaminate the material and weld area.

Preheating

Preheating the aluminum work-piece can help avoid weld cracking. Preheating temperature should not exceed 110°C (230°F); to prevent overheating, close control or temperature monitoring is advised. Use of a laser temperature indicator is very useful and recommended.

In addition, tack welding the ends of the plate to be welded helps keep the heat within the work-piece and makes the preheating more effective.

The conductivity of heat

Aluminum is an excellent conductor of heat, which requires large heat input to start welding; this is because most of the heat is often lost, including conduction of heat to the surrounding base metal. After welding has progressed for a while, much of this heat has moved ahead of the arc and preheated the base metal to a temperature requiring less welding current than the original cold plate. If the weld is continued farther toward the end of the two plates, there is no material for this preheat to go, and as such the heat is accumulated and saturates the material to such a degree that any further heat would melt away the rest of the material. Reducing the welding current is one way to address this condition. However, the welding engineer should recognize these challenges and ensure that such heat-related issues are addressed in their welding and fabrication procedures.

Some aluminum alloys containing silicon exhibit “hot short” tendencies, and they are crack-sensitive. However, these alloys are successfully welded using filler metal that contains up to 13% silicon in the alloy. Hot shortness is a property that is manifest in a range of temperatures where the solidifying weld-metal and metal that has just solidified is low in ductility and lacks sufficient resistance to the shrinking stresses. Proper choice of filler metal and welding procedures along with smaller weld bead deposits help eliminate such issues. Back step-welding techniques are often used with good results for welding these alloys.

Welding Filler Metals

The metal produced in the weld pool is a combination of filler and parent metals. The deposited weld-metal must have the strength, ductility, freedom from cracking, and the corrosion resistance required for specific design application. Table 2-8-1 lists some of the recommended filler metals commonly used for welding various aluminum alloys.

Maximum rate of deposition is obtained with filler wire or rod of the largest practical diameter while welding at the maximum practical welding current. Wire diameter best-suited for a specific application depends upon the current that can be used to make the weld. In turn, the current is governed by the available power supply, joint design, alloy type and thickness, and the welding position.

Table 2-8-1 Typical aluminum welding electrodes.

AWS class	UNS	Si	Fe	Cu	Mn	Mg	Zn	Ti	Be	Al minimum reminder	Other total
E1100	A91100	[a]	[a]	0.05–0.20	0.05	–	0.10	–	0.0008	99.00	0.15
E3003	A93003	0.6	0.7	0.05–0.20	1.0–1.5	–	0.10	–	0.0008	99.00	0.15
E4043	A94043	4.5–6.0	0.8	0.3	0.05	0.05	0.10	0.20	0.0008	99.00	0.15

Single numbers are maximum values.

[a] Silicon + Fe should not exceed 0.95%.

Welding aluminum with shield metal arc welding (SMAW) process

Aluminum is readily welded using a SMAW process, although much of the advantages obtained by other process have reduced the general preference for this process. The recommended minimum thickness for welding aluminum by SMAW is 3.2 mm.

The SMAW welding process uses direct current with the electrode held in positive polarity (DCEP). The control of moisture in the electrode covering and general cleaning of the welding surfaces are very important to accomplish good welds. The welding electrodes are removed from hermitically sealed containers prior to welding. The electrodes left over from previously opened containers are "conditioned" at 175–200°C (350–400°F) in an oven for about an hour prior to welding. To correct conditioning temperatures and time, it is best to follow the electrode manufacturer's guidance.

The material to be welded must be preheated to about 110–190°C (230–375°F), as this helps obtain good fusion and also improves weld quality. Preheating also helps avoid porosity in the weld, as any moisture remaining on the material surface is removed by preheating. The control of preheat temperature is very important as some grades of aluminum like 6XXX significantly lose their mechanical properties if heated to 175°C (350°F) or higher. Support to the weld area is often provided to reduce the risk of collapse of weld due to loss of strength of aluminum when heated.

Postweld cleaning of the flux is important as the leftover electrode covering can cause serious corrosion damages to the material, which is a situation easier to address before it becomes a problem. Cleaning is easier when the part in not in service and easy to handle.

General composition of a welding electrode is given in Table 2-8-1.

Welding aluminum with gas tungsten arc welding process

This welding process is well-suited for welding aluminum; the slower welding process is most suited for all position welding.

Aluminum welding is mostly associated with a GTAW process. This is more in case of metals with a lower thickness. Many other processes, of course, can join aluminum, but for the lighter gauges of the material, GTAW is the most suitable process. The application of this process in the aeronautical industry has been recognized for long. The popularity of aluminum in automotive applications has brought GTAW welding to more prominence. Mechanically strong and visually appealing, GTAW welding is the number one process chosen by professional welders for professional racing teams and the avid auto enthusiast or hobbyist.

Types of currents and electrodes

Both DC electrode positive and AC currents are used for welding aluminum. Argon gas is the gas of choice for manual welding.

The pure tungsten electrodes classified as EWP by AWS 5.12 or tungsten zirconium electrodes classified as EWZr-1 (tip color = brown) are the preferred electrodes for an AC welding process. The advantage of AC welding is that the cycle reversal allows for the cathodic cleaning of the surface scales and oxides, which results in good, quality welds. The electrode performs best when the tip is a hemispherical shape. The tungsten electrode tip is given a hemispherical shape "balled" by striking an arc outside the work and allowing the tip to heat and ball to the required shape; this process is called balling.

Direct current with electrode negative (DCEN) is also used for welding aluminum; this provides deep penetration and narrow weld bead. This process is good for higher thickness. The process does not have advantage of cathodic cleaning, so preweld cleaning assumes greater importance. If helium gas is used, this will result in deeper penetration compared with argon gas. Helium gas welding will also require that thoriated-tungsten electrode classified as EWTh-1 (tip color = yellow) or EWTh-2 (tip color = red) is used.

Grinding the tip of the electrodes

To get optimum arc stability, electrode tip grinding is of utmost importance. The grinding should be done with the axis of the electrode held perpendicular to the axis of the grinding wheel. Exclusive grinding wheel should be used to grind these electrodes. The use of a dedicated grinder would reduce the chances of electrode contamination from other material particles left on the grinding wheel.

The thoriated electrodes do not ball as readily as pure or zirconiated electrodes. They maintain the ground tip shape much better. If this electrode is used on AC, they tend to split affecting the weld quality.

Welding aluminum with gas-metal-arc-welding process

Power source

When selecting a power source for GMAW of aluminum, first consideration should be the method of arc transfer. A choice is to be made between a spray-arc or pulse-arc metal transfer system.

Spray-Arc Transfer

Constant-current (CC) and constant-voltage (CV) machines can be used for spray-arc welding. Spray-arc takes a tiny stream of molten metal and sprays it across the arc from the electrode wire to the base material. For thick aluminum that requires welding current in excess of 350 A, CC process produces optimum results.

Pulse-Arc Transfer

Pulse transfer is usually performed with an inverter power supply. Newer power supplies contain built-in pulsing procedures based on filler-wire type and diameter. During pulsed GMAW process, a droplet of filler metal transfers from the electrode to the work-piece coinciding with each pulse cycle of current. This process produces positive droplet transfer and results in less spatter and faster welding speeds than a spray-transfer welding process. Using the pulsed GMAW process on aluminum also gives better-controlled heat input, ease in manipulating the weld-metal in out-of-position welds, and allows the operator to weld on thin-gauge material at low wire-feed speeds and currents.

Wire feeder

The preferred method for feeding soft aluminum wire is the push-pull method, which employs an enclosed wire-feed cabinet to protect the wire from the environment. A constant-torque variable-speed motor in the wire-feed cabinet helps push and guide the wire through the gun at a constant force and speed. A high-torque motor in the welding gun pulls the wire through and keeps wire-feed speed and arc length consistent.

In some shops, welders use the same wire feeders to deliver steel and aluminum wire. In this case, the use of plastic or Teflon liners help ensure smooth and consistent aluminum-wire feeding. For guide tubes, use of chisel-type outgoing and plastic incoming tubes to support the wire as close to the drive rolls as possible prevents the wire from tangling. When welding, keeping the gun cable as straight as possible minimizes wire-feed resistance. Correct alignment between drive rolls and guide tubes is important to prevent aluminum wire shaving.

Drive rolls specially designed for aluminum must be used. The tension on the drive roll allows for the delivery at an even rate of wire-feed into the weld. The control on the tension is of importance as any excessive tension will deform the wire and cause rough and erratic feeding; on the contrary, slack tension would results in uneven feeding. Both conditions can lead to an unstable arc and weld porosity.

Welding guns

Welding guns must be kept clean and free from dirt and spatters. A separate gun liner for welding aluminum is recommended. Both ends of the liner must be held in restraint to eliminate gaps between the liner and the gas diffuser on the gun. This would also prevent wire from chaffing.

The lines must be changed frequently to reduce the possibility of collecting abrasive aluminum oxide, which can cause wire-feeding problems.

The contact tip diameter should be approximately 0.4 mm (0.015 in.) larger than the filler wire diameters, to allow for the free movement of the wire when the tip is expanded due to heat and reducing the tip diameters, which often turns into an oval-shaped orifice. To keep control over heat-related expansion and other difficulties, the welding guns are water-cooled if welding current exceeds 200 A.

Welding technique

The push technique

With aluminum welding, the practice of pushing the gun away from the weld puddle rather than pulling it will result in better cleaning action, reduced weld contamination, and improved shielding-gas coverage. This also controls heat in the parent metal and prevents overheating and collapse at the end of the weld.

Travel speed

Aluminum welding needs to be performed "hot and fast." Unlike steel, the high thermal conductivity of aluminum dictates use of higher amperage (higher heat) and voltage settings and higher weld-travel speeds. If travel speed is too slow, the welder risks excessive burnthrough, particularly on thin-gauge aluminum sheet.

Shielding gas

Argon gas, due to its good cleaning action and penetration profile, is the most common shielding gas used when welding aluminum. Welding 5XXX-series aluminum alloys, a shielding-gas mixture combining argon with helium up to 75% helium maximum, will minimize the formation of magnesium oxide.

Welding wire

Welding filler-wire selection should be a carefully made decision. Selection should match the melting temperature of the wire and parent metal. It is common to use welding wire of larger diameter because heavier feed rate for wires of 2.5 mm to 1.6 mm (3/64- or 1/16-in.) are often used, but it must be considered depending on the overall weld joint design. Thin-gauge material is often welded with 0.9 mm (0.035 in.) diameter wire combined in a pulsed-welding mode, where the feed rate is between 2.5 and 7.5 m per minutes.

Convex-shaped welds: In aluminum welding, crater cracking causes most failures. Cracking results from the high rate of thermal expansion of aluminum and the considerable contractions that occur as welds cool. The risk of cracking is greatest with concave craters, as the surface of the crater contracts and tears as it cools. Therefore, welders should build-up craters to form a convex or mound shape. As the weld cools, the convex shape of the crater will compensate for contraction forces.

Friction stir welding

As stated earlier, the typical property of aluminum to form tenacious oxide film. The oxide film makes it difficult, but not impossible, to weld. For this reason, the electric resistance welding of aluminum is difficult though not impossible. As we have seen so far, there are numerous ways to use flux and inert gas, and also the action of electrical polarity to remove this impediment from welding cycle.

The process of FSW involves joining the metal without fusion or addition of filler metal. The process results in strong and ductile welds. The process is suited to weld components that are flat and long. Frictional heating and mechanical deformation create the weld. The circular rotating tool rotates and the friction causes heat at approximately about 80% of the melting point of the metal. The heat is primarily generated by friction between the rotating tools, the shoulder of which rubs against the workpiece. There is volumetric distribution of heat from adiabatic heating due to the deformation near the pin. Adiabatic heating is caused by pressure change; there is no heat transfer in the environment. Heat is supplied by friction, which in this process is used to heat the faying surfaces of the material to be welded. Welding parameters are adjusted so that the ratio of frictional-to-volumetric heating decreases as the workpiece thickness increases. This allows for sufficient heat input per unit length.

As the process describes itself, the central nugget region containing the onion ring flow is the most deformed region of the weld. The thermomechanically affected zone lies between the HAZ and the nugget, where the grains of original microstructure are retained but in a deformed state.

The ability to weld efficiently depends on the design of the tool. More development is being done, with TWI in Abington, Cambridge, United Kingdom leading in this effort; more detail can be obtained from their publications on the subject.

Nickel alloys

A brief introduction to the commercial nickel and nickel alloys is given here. Generally, the specific alloy type or grades have proprietary names and compositions; the following is a general description. There is a virtual continuum of austenitic alloys containing Fe, Cr, Ni, and Mo. The distinction between highly alloyed stainless steels and lower-alloyed nickel-base alloys is somewhat arbitrary.

Based on the UNS numbering system, the alloy numbers starting with a prefix “N” are grouped with the nickel-based alloys discussed in this section. Those beginning with “S” are grouped with the austenitic stainless steels. There are several common high-nickel cast alloys used in the oil field.

Commercially pure (99.6%) and wrought nickel has UNS number N02200; and ASTM B 160-63, 725, and 730 manufacturers should be consulted for more specific details.

The next group is an alloy of nickel and copper with UNS numbers N 04400, N 04404, N 04405, N 05500, etc. These alloys have excellent corrosion resistance to a broader environment, although some of them are specifically useful in specific environment, for example, UNS C 71500 has excellent resistance of corrosion in a marine environment. Technically, these are copper alloyed with nickel. These alloys are often called “cupro-nickel alloys.” In these alloys, the percentage of copper exceeds percentage of nickel.

The other groups of nickel alloys with additions of iron (Fe) are particularly designed to work in high-temperature services and resist chloride stress corrosion. The UNS numbering is generally N 06600, which is a solid solution alloy of Ni, Cr, Mo, Fe, and Nb.

Heat treatment

Solid-solution nickel-based alloys are generally used in the annealed or annealed and cold-worked condition. These alloys are not designed for strengthening by heat treatment.

Mechanical properties

The maximum yield strength is governed by alloy composition, the cold-working characteristics of the alloy, the maximum yield strength permitted by the application, and the ductility specified. Room-temperature yield strengths can range from about 210 to 1380 MPa (30 to 200 ksi), depending on composition and the degree of cold-working. The minimum yield strength for tubing is generally in the range of 760–970 MPa (110–140 ksi). Casing and liners often have higher yield strength.

Fabrication

Annealed alloys can be welded using GTAW, SMAW, GMAW, SAW, and FCAW.

Cold-worked alloys are usually not welded because the mechanical strength of the weldments would be lower than that of the cold-worked region. The mechanical properties of cold-worked tubing, especially in thicker sections, can vary through the section.

The high-nickel alloys are more prone to casting defects such as hot tears, cracking, porosity, and gassing. These defects can appear at any stage of the manufacturing process such as shakeout, heat treating, machining, or final pressure testing. Although the wrought high-nickel alloys are routinely welded and some even hardfaced, welding the cast alloys is considerably more difficult. Stringent specifications developed in close cooperation with the foundry have typically been used to optimize weldability and casting integrity. For production of good quality casting, the foundry processes, raw material quality, filler material composition, weld repair procedures, and heat treatment are closely controlled and monitored.

Precipitation hardenable nickel-based alloys

Precipitation hardenable nickel chromium alloys often contain a fair amount of iron (Fe); these alloys are used for corrosion resistance, higher strength, and excellent weldability.

Heat treatment of PH nickel alloys

These alloys are usually used in solution-annealed, solution-annealed and aged, hot-worked and aged, or cold-worked and aged conditions.

In sour gas applications, the heat treatment of UNS N07718 is typically selected to give good toughness, yield strength, and corrosion resistance. A solution anneal followed by a single-step aging is often used. For sour gas applications, UNS N07716 and N07725 are solution-annealed and aged.

Mechanical properties

At room temperature, the specified minimum yield strengths of these alloys varies from 340 to 1030 MPa (50 to 150 ksi).

Welding

Overall, as with all CRAs, welding hygiene is of paramount importance. The care and attention to the following issues will constitute good weld hygiene practice.

Cleanliness of the parts to be welded
Maintenance and monitoring of interpass temperature
Accuracy and cleanliness of bevel profile
Proper weld bead profile
Use of appropriate welding consumables
Control of heat input
Welder qualification
Correct stress relief
Correct shielding gas composition and flow rate
Correct backing gas composition and flow rate
When welding dissimilar material, welder is to consider the resultant microstructure and composition of the final weld joint.
Welding process like TIG (GTAW), MIG/Pulsed MIG (GMAW), and autogenous welding are typically used.

UNS N07718, N07716, and N07725 can be welded by GTAW process. Repair welding UNS N07718 in the aged condition is possible, but the possibility of microcracking is increased. The recommended postwelding heat treatment is solution annealing and aging.

UNS N07750 is not normally welded or repaired in the aged condition.

Titanium alloys

Titanium alloys have relatively high tensile strength and toughness while being lightweight, corrosion resistant, and have the ability to withstand extreme temperatures. The higher cost of the material and the difficulty in working with it are the limiting factors of these alloys.

Titanium and its alloys provide corrosion resistance and a range of mechanical properties; they possess yield strength in the range of 40–170 ksi (276–1172 MPa). The alloys are classified by their resultant microstructure based on their chemistry and are identified as (α) alpha, (α-β) alpha-beta, or (β) beta alloys. Each of these alloy systems get their specific properties through different heat treatment cycles they receive, such as annealing or solution treating and aging.

The (α) alpha alloys exhibit single-phase microstructure; hence, their properties are only influenced by their chemistry.

As the name suggests, the (α-β) alpha-beta alloys are a two-phased microstructure system. Their properties can be influenced by a variety of heat-treatment cycles.

Beta alloys (β) are precipitation-hardened systems, and they offer a wide range of mechanical properties.

Titanium alloys have extensive use in aircraft and space industry; however, they have had limited use in oil and gas industry, but their use is expanding as a result of their low density and excellent corrosion resistance in H_2S and chloride environments. Stress joints, packers, safety valves, and other completion components have been manufactured from a variety of titanium grades.

Heat treatment

As stated before, the titanium alloys generally fall into one of three broad categories based on their crystallographic structures: (α) alpha, (α-β) alpha/beta, and (β) beta. Commercially pure titanium is classified as alpha.

Alpha (α) titanium

These alloys are generally used in the annealed or stress-relieved condition. They are considered fully annealed after heating to 675–788°C (1250–1450°F) for 1–2 h. Stress relieving can be performed at 480–590°C (900–1100°F) for ½–1 h.

Alpha (α) alloys are generally fabricated in the annealed condition. All fabrication techniques used for austenitic stainless steels are generally applicable. Weldability is considered good if proper shielding is employed. Contamination of the weld by oxygen or nitrogen is to be avoided.

Alpha/beta (α-β) titanium

These alloys are generally used in the mill-annealed or solution-treated plus aged condition. Annealing is generally performed at 705–845°C (1300–1553°F) for 1/2–4 h. Solution treating is generally performed at 900–980°C (1650–1800°F) followed by an oil or water quench. Aging is generally performed at 480–705°C (900–1300°F) for 2–24 h. The precise temperature and time are chosen to achieve the desired mechanical properties. To achieve higher fracture toughness or crack growth resistance, these alloys can be processed to an acicular alpha via working and/or final annealing above the alloy's beta transition temperature.

Weldability of this alloy depends on the specific alloy. Generally, the fabrication is carried out at elevated temperatures, which is followed by heat treatment. These alloys have very limited ability to be cold-formed.

Beta (β) titanium

Beta (β) alloys are generally used in the solution-treated and aged condition. Cold-working and direct-age treatments can increase higher yield-strength of these alloys above 1200 MPa (180 ksi). Annealing at 730–980°C (1350–1800°F) and solution treating are generally performed to control ductility. Aging is typically carried out at 480–590°C (900–1100°F) for 2–48 h to obtain the desired mechanical properties. A process called duplex aging is also used to improve the response to aging. Duplex aging is performed in two cycles; in the first cycle, the material is heated between 315°C and 455°C (600°F and 850°F) for 2–8 h followed by the second age cycle at 480–590°C (900–1100°F) for 8–16 h.

Beta alloys can be fabricated in similar ways as the alpha alloys discussed before; they can be cold-formed in the solution-treated condition. Because of the higher yield strength of β alloys, increased forming pressure is required. Weldability of these beta (β) alloys is good. Aging is carried out after welding to increase the strength. The welding process produces an annealed condition exhibiting strengths at the low end of the beta alloy range.

Weld defects and inspection

9

Weld quality

Quality is a relative term, so different weldments and individual welds may have different quality levels depending on the service requirements. Quality includes factors such as hardness, chemical composition, and mechanical properties.

Acceptable Quality means that a weldment is:

(1) Adequately designed to meet the intended service for the required life
(2) Fabricated with specified materials and in accordance with design concepts
(3) Operated and maintained properly

Acceptance standards

The quality of weld and thereby the weldments is designed in the initial process of the engineering design. The design specification or code defines the minimum acceptable level of flaws in the weld, or in other words the maximum length, area, and depth of certain types of flaw that can be accepted without compromising the functional ability of the weldments. This is possible only when knowledge of the test methods, their limitations, and the ultimate demands of the weldments is known to the designers. Several inspection and testing guidelines and some mandatory specifications are available for reference. They all address the issue within the scope of their mandated technical jurisdictions. For example, ASME B 31.3 for pressure piping, API 1104 for pipeline welding, and AWS D 1.1 for structural design and welding are some of the specifications. Then there are other specifications that specifically deal with the specific challenges of the test methods, such as ASTM E 317 for evaluating performance characteristics of ultrasonic pulse-echo testing system without the use of electronic measuring instruments; European Norm (EN) 10160 for ultrasonic testing of steel flat products using reflection method of thickness equal to or greater than 6mm; and ISO 12094 for UT for the detection of laminar imperfections in strip/plates used in the manufacture of welded tubes. Other examples include ASTM A 578, which is a standard for straight-beam ultrasonic examination for special applications and ASME SA 275 method for magnetic particle examination of steel forgings. ASME section specifies most of the nondestructive testing associated with welds and materials used for pressure vessels and components.

Fabrication codes and standards give the minimum requirements to ensure that a welded fabrication will operate safely in service. Standards should not be encroached upon or acceptance level diluted without sound engineering judgment and backing. Where the work is required to meet a specific standard, the requirements of such specification must be strictly followed, unless written clarification or deviation is obtained from the client or the specification-issuing body.

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Weld quality is verified by nondestructive examination. Acceptance standards are related to the method of examination. All deviations should be evaluated and the acceptance or rejection of a weld should be based on the acceptance standards. Determination of the overall quality requirements is a major consideration involving design, fabrication, operation, and maintenance.

Discontinuities in fusion-welded joints

Discontinuities may be related to the welding procedure, the process, design, or metallurgical behavior. Process, procedure, and design discontinuities affect the stresses in the weld or heat-affected zone (HAZ). Metallurgical discontinuities may also affect the local stress distribution and alter mechanical or chemical (corrosion resistance) properties of the weld or HAZ.

Discontinuities may amplify stresses by reducing the cross-sectional area. The more serious effect though is stress concentration—stresses are concentrated at notches, sharp corners, abrupt changes in profile, and (especially) cracks. Discontinuities should be considered in terms of:

1. Size
2. Acuity or sharpness
3. Orientation with respect to the principal working stress
4. Location with respect to the weld, joint surfaces, and critical sections of the structure

On these serious implications, it is important to know that imperfection sizing is a critical activity that a welding engineer has to know and master to be able to make decisions on the acceptability of the certain size and type of discontinuity that will not cause failure of the structure. The following is the method used to determine the sizes of discontinuities in welds.

Sizing of discontinuities

Sizing discontinuities to determine if it is acceptable or not is essential. It is one of the responsibilities of welding engineer. The need for effective sizing and critical measurement of planar discontinuities cannot be overemphasized. This activity becomes very important when dealing with welds that are subject to stresses causing fatigue, and carbon steel and alloy steel weldments that are in low temperature service, which can lead to brittle fracture. The maximum size of discontinuity to prevent brittle fracture can be determined. To calculate the effective imperfection of size, the following parameters can be used;

$$\bar{a} = C\left(\delta/\varepsilon_y\right) \qquad [1]$$

where:

$\bar{a}$ is the effective imperfection size parameter.

$$C = (1)/2\pi\left\{\sigma_a/\sigma_y\right\}^2 \quad \text{for}\, \sigma_a/\sigma_y \le 0.5 \qquad [2]$$

Or

$$C = (1)/2\pi\left\{\left(\varepsilon_a/\varepsilon_y\right) - 0.25\right\} \quad \text{for}\, \sigma_a/\sigma_y > 0.5 \qquad [3]$$

Where:

σ_a = Maximum effective applied tensile bending stress, MPa
σ_y = Specified minimum yield strength of pipe, MPa
ε_a = Maximum effective applied tensile bending strain
δ = CTOD fracture toughness value, mm
ε_y = Elastic yield strain = σ_y/E (E = Young's modulus)

Classification of weld joint discontinuities

Weld discontinuities can be classified based on the welding process or welding procedure, metallurgical, or design related.

Included in the first group of welding processes or procedures related the discontinuities are flaws such as:

Undercut
Concavity or convexity
Misalignment
Improper reinforcement
Excessive reinforcement
Burnthrough
Overlap
Incomplete penetration
Lack of fusion
Shrinkage
Surface irregularity
Arc strike
Inclusions like slag or tungsten inclusion
Oxide film
Arc craters
Spatters

In the metallurgical group, the following types of discontinuities would be found:

Cracks or fissures, which may be hot cracks, cold or delayed cracks, stress cracks, or cracks due to reheat
Lamellar tearing
Porosity: spherical, elongated, or worm holes
HAZ alteration of microstructure
Weld-metal and HAZ segregation
Base plate lamination

The design-related discontinuity group might include discontinuities such as stress concentration due to changes in sections or type of weld joint design.

Typical weld defects

Typical weld defects are shown in Figure 2-9-1. These are some of the commonly detected defects in a typical weld; however, their presence, variance, and appearance differ according to the welding process. The soundness of any weld is dependent on the type of defects and its analysis with respect to the end use of the weldments.

The analysis of the seriousness of any discontinuities should be made on the basis of their shape; the terms used to describe these are *planar* or *three-dimensional*. The cracks, laminations, incomplete fusion, and inadequate penetration that have more pronounced stress amplification are the planar-type discontinuities. Inclusions and porosity would be the examples of three-dimensional discontinuities.

While characterizing these discontinuities, the size, acuity (sharpness), and orientation with respect to the principal stress and residual stress, the proximity to the weld, and the surface of the material are essential factors to consider.

As there are several types of constructions, they generate several types of weld defects and combinations of definitions; these definitions also vary according to the use of the inspection process and the specification in use. Generally, all these are based on the end use of the weldments. The following is the descriptions of some of the basic weld discontinuities.

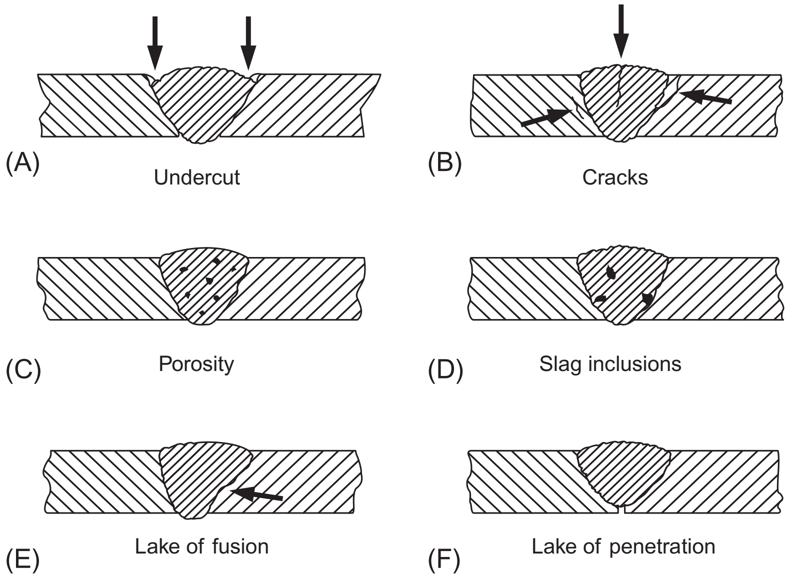

Figure 2-9-1 Typical weld defects.

Porosity

Porosity is the result of gas being entrapped in solidifying weld-metal; it is generally spherical but may be elongated. Uniformly scattered porosity may be scattered throughout single-weld passes or throughout several passes of a multipass weld.

Faulty welding technique, defective materials, or poor weld hygiene generally cause porosity. Cluster porosity is a localized grouping of pores that can result from improper arc initiation or termination. Linear porosity maybe aligned along a weld interface, root, or between beads. It is caused by contamination along the boundary.

Piping porosity is elongated and, if exposed to the surface, indicates the presence of severe internal porosity. Porosity has little effect on strength, some effect on ductility, and significant effect on fatigue strength and toughness. External porosity is more injurious than internal porosity because of the stress concentration effects.

The porosity is considered as spherical and nonplanar imperfection; thereby, it is not a serious threat to weld in normal loading and even in fatigue conditions. The tolerance of porosity in such conditions is very liberal, and often up to 5% porosity in a standard radiograph length is accepted. However, if the weld is required to have good toughness to resist brittle fracture at lower temperatures, especially where the Charpy impact values of the weld-metal is required to be 40 J (30 ft lbf) or higher, the porosity is treated as a planar imperfection.

Inclusions

Slag inclusions are nonmetallic particles trapped in the weld-metal or at the weld interface. Slag inclusions result from faulty welding technique, improper access to the joint, or both. Sharp notches in joint boundaries or between weld passes promote slag entrapment.

With proper technique, slag inclusions rise to the surface of the molten weld-metal. Tungsten inclusions are tungsten particles trapped in weld-metal deposited with the GTAW process. Dipping the tungsten electrode in the molten weld-metal or using too high current that melts the tungsten can cause inclusions.

Incomplete fusion

Incorrect welding techniques, improper preparations of materials, or wrong joint designs promote incomplete fusion in welds. Insufficient welding current, lack of access to all faces of the joint, and insufficient weld joint cleaning are additional causes. This is a stress-concentrating flaw and can in most cases initiate cracks.

Inadequate joint penetration

When the actual root penetration of a weld is less than specified, the discontinuity at the root is called inadequate penetration.

It may result from insufficient heat input, improper joint design (metal section too thick), incorrect bevel angle, or poor control of the arc.

Some welding procedures for double-groove welds require back-gouging of the root of the first weld to expose sound metal before depositing the first pass on the second side to insure that there is not inadequate joint penetration.

Like incomplete fusion discussed before, incomplete penetration is a stress-concentration point, and cracks can initiate in the unfused area and propagate as successive beads are deposited. Cyclic loading can initiate catastrophic failures from incomplete penetration.

Undercut

Visible undercut is associated with improper welding techniques, excessive currents, or both. It is a grove running parallel along the toe of the weld, either on the root or the faces side of the weld. The undercuts are of varying depth and area, but it is their relative depth and length that are of importance as acceptable or not acceptable flaws.

Undercut creates a mechanical notch at the weld toe. In addition to the stress raiser caused by the undercut notch, fatigue properties are seriously reduced.

Underfill

Underfill results from the failure to fill the joint with weld-metal, as required. It is corrected by adding additional layers of weld-metal. If left uncorrected, this becomes a stress concentration point and may subsequently be a cause of failure.

Overlap

Incorrect welding procedures, wrong welding materials, or improper preparation of the base metal causes overlap. It is a surface discontinuity that forms a severe mechanical notch parallel to the weld axis. Fatigue properties are reduced by the presence of the overlap, as they are cable of initiating cracks.

Cracks

In most cases, cracks occur when the localized stresses exceed the tensile strength of the material. Cracking is often associated with stress amplification near discontinuities in welds and base metal, or near mechanical notches associated with weldment design.

Hot cracks develop at elevated temperatures during or just after solidification. They propagate between the grains. Cold cracks develop after solidification as a result of stresses. Cold cracks are often delayed and associated with hydrogen embrittlement. They propagate both between and through grains. Throat cracks run longitudinally in the face of the weld and extend toward the root. Root cracks run longitudinally and originate in the root of the weld. Longitudinal cracks are associated with high welding speeds (such as during SAW) or with high cooling related and restraint.

Transverse cracks are perpendicular to the weld and may propagate from the weld-metal into the HAZ and base metal. Transverse cracks are associated with longitudinal shrinkage stresses in weld-metal that is embrittled by hydrogen. Crater cracks are formed by improper termination of the welding arc. They are shallow hot cracks.

Toe cracks are cold cracks that initiate normally to the base metal and propagate from the toes of the weld where residual stresses are higher. They result from thermal shrinkage strains acting on embrittled HAZ metal.

Underbead cracks are cold cracks that form in the HAZ when three conditions are met:

(1) Hydrogen in solid solution
(2) Crack-susceptible microstructure
(3) High residual stresses

None of these can be detected by visual inspection and do not normally extend to the surface.

Cracking in any form is an unacceptable discontinuity and is the most detrimental type of welding discontinuity. Cracks must be removed.

Surface irregularities

Surface pores are caused by improper welding techniques such as excessive current, inadequate shielding, or incorrect polarity. They can result in slag entrapment during subsequent welding passes.

Variations in weld surface layers, depressions, variations in weld height or reinforcement, nonuniformity of weld ripples, and other surface irregularities can indicate that improper welding procedures were followed or that welding technique was poor.

Base metal discontinuities

Base metal properties such as chemical composition, cleanliness, laminations, stringers, surface conditions, and mechanical properties can affect weld quality. Laminations are flat, elongated discontinuities found in the center of wrought products such as plate. They may be too tight to be detected by ultrasonic tests. Delamination may occur when they are subjected to transverse tensile stresses during welding.

Lamellar tearing is a form of fracture resulting from high stress in the through-thickness direction. Lamellar tears are usually terrace-like separations in the base metal caused by thermally induced shrinkage stresses resulting from welding.

Weld profiles affect the service performance of the joint. Unfavorable surface profiles on internal passes can cause incomplete fusion or slag inclusions in subsequent passes.

Designing weld joints

A welding engineer will be required to support activities of the design team and will be called upon to analyze the structure soundness of the members or evaluate best ways to eliminate possible flaws in the structure. This requires that the welding engineer is well aware of the factors responsible for structural stability and soundness of its members, the allowing stress and effect of various loadings, and apply them to the welding part to design the most compatible weldments.

The welding engineer will be required to design weldments to meet the specified structural properties. The weld does not stand isolated from the members of the weldments; it has to be an integral part of the entire structure and function accordingly. With the knowledge of the subject discussed in the previous section and chapters, it is possible for an educated engineer to address the challenges of structural stability in terms of metallurgical and welding knowledge to success.

However there are other factors associated with successful designing of weldments. Some of these details are discussed in some length in the subsequent chapters and sections of this book.

One of the important parts of designing is the knowledge of structural engineering and analysis of various stresses associated with any structures. In designing the weld, all principles of a structural design have to be evaluated and married to the properties of the material and the weld. This emphasizes the proper selection of material for any specified project. The performance of a structural member is dependent on the properties of the material and characteristics of the particular section.

The engineers should be able to compute the applied forces on a specific structural member and be able to determine the required strength to resist those forces to prevent the member from failure.

The approach of the engineer should be to take into account and utilize available resources to reduce the cost of the new design or redesign of existing design to upgrade its performance.

The structural integrity of the designed member should be the prime concern of the designers. For this, the designers should consider the quality of available workmanship, load factors, deterioration from corrosion and damages over the life period of the designed structure, safety factors, and regulatory requirements.

Basis for welded design

Designing for strength and rigidity would require that the structural member must be evaluated to meet following two parameters to meet the service demands.

1. It should not break or yield upon loading with factor of safety applied.
2. The loading could be static or dynamic, or sometimes the load may be just the weight of the structure itself called *dead load.*

In designing, such terms as stress, load, member strain, and deformation is commonly used. They also appear in the engineering formula used for calculations by design engineers. Some of these are discussed here in context with weld design.

In the design process, welding engineers may be required to find out the internal stress of the deformation, determining the external load that will be applied on the member and if that load will exert stresses beyond the allowable stress. It is normally desirable to keep the deflection to the minimum possible. A simple step is to ensure the stiffness of a cantilever beam; the following relationship of applied forces, length of the beam moment of inertia, and modulus of elasticity compute the amount of vertical deflection at the end of the beam.

$$\Delta = \left(FL^3\right)/(3EI) \qquad [4]$$

Where:

Δ = The deflection
F = Applied load or force
L = Length of the beam
E = The modulus of elasticity of the material
I = The moment of inertia of the beam section

In this equation, the value of E and I should be largest possible to achieve optimum position that has minimum deflection. For steel, the modulus of elasticity is taken as 30×10^6 psi, where I is the moment of inertia of the beam. For this to be large, the cross-section of the beam should be large enough to limit the deflection to a permissible value. This is a simple condition; there are several out-of-plane forces applied on any member, and those are the ones that need to understood and considered in calculation for designing.

There are five basic types of loading. When one or more of these loads are applied, they induce stress in addition to any residual stress contained within the material. These stresses result in strains or movements within the member, the magnitudes of which are governed by the modulus of elasticity of the metal; it is denoted by letter E, and there is always some movement when any load is applied.

We shall briefly discuss all five types of stress in this discussion on designing.

Tension

Most common loading on any member is the tensile stress. A straight bar under simple axial tensile force has no tendency to bend. The load causes the axial strain and elongation of the bar. The only requirement would be to have an adequate cross-sectional area to withstand the load.

Compression

Compression load causes buckling; the example of this would be the column that is loaded through its center of gravity, under the resulting simple axial stresses. If the column is a slender structure, the slenderness is defined as the ratio of length-to-radius of the column; it will start to bow laterally as the load is increased. This would happen at a stress much lower than the yield strength of the material.

On further loading, the column that is now eccentric to the axis of the load will cause a bending moment. At this point, if the load is made sturdy the column will remain stable due to the combined effect of axial stress and the bending moment. However if the load were increased, then a critical point would be reached in the curvature of the column's axial bending, where the column will buckle and fail. From a welding point of view, as the column deflects under the load, a bending moment can develop in semi rigid or rigid welded end connections.

The compressive strength in the column described here would be dependent on the cross-section area and the radius of gyration.

To determine the compressive load that a column could support without buckling, the allowable compressive stress is multiplied by the cross-sectional area.

The distance from the neutral axis of the section to an imaginary line in the cross-section about which the entire area of the section could be concentrated and still have the same moment of inertia about the neutral axis of the section is the radius of gyration. This indicates the ability of the column to resist buckling. The radius of gyration can be determined by following equation.

$$\mathrm{r} = (I/A)^{0.5} \qquad [5]$$

Where:

r = Radius of gyration
I = Moment of inertia about the neutral axis
A = Cross-sectional area of the member

It is important to use the minimal value for the radius of gyration in ratio to the unbraced length of the member. The smaller of the two moments of inertia about axes x-x or y-y is used in the calculation.

Often, industrially published data is used to obtain the values of compressive stress of a given radius of gyration. American Institute of Steel Construction (AISC) publishes such data for a vast number of structural steels.

Bending

Bending can occur under uniform or nonuniform loading. Loading within the elastic range results in zero-bending stresses along the neutral axis of the member. This stress increases toward the outer fibers of the material.

As we know, in a simply supported beam, the bending moment decreases along the length as we move toward the end of the beam. This in turn reduces the compressive as well as tensile stresses that are the reduction of bending stress. In an example of a beam in the shape of an I-section, the bending stress in the flange of the beam will decrease as we move toward the end of the beam. If we consider a short length of the beam, where the tensile force is F_1 and F_2 applied at these two points, we will note that there is a clear difference between these two tensile forces. A tensile force F is the product of tensile stress (σ_t) and flange cross-sectional area (A). The decrease in the tensile force F in the flange causes a corresponding shearing force between the flange of the beam and the web of the beam. This shear force is transmitted by the fillet weld that joins the two (the web and the flange) together. The upper flange that is in compression mode has a similar shear force acting on it.

Another way the bending problem manifests itself is called deflection. Deflection is often associated with beams that have larger span in relation with the depth of the beam. To meet the stiffness requirements, the beam depth should be as large as practical. Where such large beam depth is not possible but beam stiffness must be achieved, it is good engineering practice to design attachment of stiffener plates by welding the web and flange of the beam.

Shear

Shear stresses can be both horizontal and vertical; they also develop diagonal tensile as well as diagonal compressive stresses. The shear capacity of a beam is dependent on the slenderness ratio; this means that the cross-sectional area of the beam is one of the factors. For the web of a welded beam, if this ratio is less than 260, the vertical shear load is resisted by pure beam shear without lateral buckling to a level of loading well above where unacceptable deflection will develop. This implies that the design should be based on keeping the shear stress on the gross area of the web below the allowable value of 0.4 σ_y to prevent shear yielding.

In cyclic loading to a level that would initiate web shear buckling, each application of the critical load will cause a breathing action of web panels. This would cause out-of-plane bending stresses at the toes of the web-to-flange fillet welds and stiffener welds. These cyclic stresses would eventually cause fatigue cracking; the web stresses in these conditions should be limited to the values where shear buckling can be kept out.

In a flange joining the web of a beam fabricated by welding, the shear stress in the weld will be computed using the following equation.

$$W_s = (Vay)/(In) \quad [6]$$

Where:

W_s = Load per unit length of weld
V = External shear force on the member at this location
a = Cross-sectional area of the flange
y = Distance between the center of gravity of the flange and the neutral axis of bending of the whole section
I = Moment of inertia of whole section about the neutral axis of bending
n = Number of welds used to attach the web to the flange

Torsion

Torsional resistance increases significantly with closed cross-sectional frames. The torsional resistance of a solid rectangular section that has width several times that of the thickness of the member can be calculated by following equation.

$$\mathrm{R} = \mathrm{bt}^3/3 \quad [7]$$

Where:

R = Torsional resistance (in.^{4})
b = Width of the section (in.)
t = Thickness of the section (in.)

The total angular twist or rotation of a member can be estimated by the equation given here.

$$\theta = \mathrm{Tl/GR} \quad [8]$$

Where:

θ = The angle of the twist, in radians
T = Torque, lbf in.
l = Length of the member, in.
G = Modulus of elasticity in shear, psi (12×10^6 for steel)
R = Total torsional resistance, in.^{4}

The unit angular twist (Φ) is equal to the total angular twist (θ) divided by the length l of the member.

Cylindrical or spherical pressure vessels including hydraulic cylinders, gun barrels, pipes, boilers, and tanks are commonly used in industry to carry both liquids and gases under pressure. They can be in various shapes and types, for example, they may be open-ended, cylinder-like pipe, or closed-ended cylinders like ASME pressure vessels, or a sphere. When these pressure vessels are exposed to pressure, the material is subjected to pressure loading, developing stresses from all directions. The stresses resulting from this pressure are functions of the radius of the element under consideration, the shape of the pressure vessel, and the applied pressure.

Calculations similar to those described earlier are carried out to establish the integrity of cylindrical equipment. These may be a pipeline or a pressure vessel working under either internal or external (vacuum) pressure. The stresses that work on these fall into a combination of the five types of stresses discussed before.

The internal pressure often caused by hydrostatic pressure in a cylinder causes stresses in three dimensions:

1. Longitudinal stress (axial) σ_L
2. Radial stress σ_r
3. Hoop stress σ_h

All three stresses are normal stresses, and they are to be computed to meet specific design requirements.

Stresses in pressure vessels

The stresses applicable in a pressure vessel are grouped in two types: the thin wall and method based on elasticity solution.

The most common method of analysis is based on a simple mechanics approach and is applicable to "thin wall" pressure vessels. The thin wall is defined as the vessel whose inner radius (r)-to-wall thickness (t) ratio is equal to or greater than 10.

The second method is based on elasticity solution and is always applicable regardless of the r/t ratio and can be referred to as the solution for "thick wall" pressure vessels. Both types of analysis are addressed in various pressure vessel codes like ASME section VIII, BS 1500, BS 5500, IS 2825, etc. Readers are advised to refer to these codes and standards to adequately familiarize themselves with details and to meet specific code requirements.

Pipelines

As stated earlier, pipelines have similar stresses as pressure vessels; however, buried lines are subject to another stress in the form of upheaval buckling (UHB), often caused due to the soil restraints. If the sturdiness of pipe design is not able to counter the translated effect of thermally induced axial expansion, the resulting expansion and out-of-straightness causes UHB. Should lateral restraint exceed vertical uplift restraint—a product of pipeline weight per unit length, pipeline bending stiffness, and soil cover—a pipeline may become unstable and dramatically move in the vertical plane. This phenomenon is described as UHB. If, however, the vertical uplift restraint exceeds lateral restraint, the resultant pipeline expansion would feed into buckling sites in the lateral plane.

The occurrence of UHB is a result of pipeline out-of-straightness, which may be introduced as a result of trench bed imperfections, straightness of the pipe, and misalignments of the girth weld. Prediction of UHB is key to the safety and integrity of pipeline projects.

Predicting possible UHB is also key to proper design of a buried pipeline and can be complicated because of uncertainties in the soil properties and pipeline's vertical profile as well as the project specific requirements. If not predicted and mitigated, UHB can result in significant damage to the pipeline.

Welding and quality assurance

Welding with its multiple variations and interplay of materials and processes is unique in its quality assurance challenges. Welding engineering is also uniquely intertwined with its art form of practice of welding itself, the artisan, or the trade part of the welding. Because the application of welding is equally varied in the industry, the level of acceptance of its quality also varies. This vast and unique diversity makes us ponder on what constitutes an acceptable level of welding quality. Of course it cannot be one simple specification that fits all.

The industries and commercial guilds over the years have developed their own criteria for establishing their acceptable level of quality. Over the years, more generic common points have emerged to establish a universally acceptable set of activities that would apply to nearly all industries, without considering specific trade or process. Such universality is seen in the application of ISO 9000 series of specifications. ISO 9000 series of quality assurance system specifications are very generic as they dwell on very fundamental principles of quality assurance that must be met by businesses to conduct their activities and ensure their clients that basic principles are being met.

While the quality assurance approach is vital and important for international commerce to flow, it is not enough for the quality assurance of specific processes like welding. This uniqueness of welding was recognized long ago by welding experts and quality assurance bodies. This resulted in development of earlier specifications like BS 5750 (a predecessor of ISO 9000) and bridging specification BS 5400 before the present set of EN specifications; this recognition has led to developing a more welding-oriented Quality Management System (QMS).

The main thrust of the Welding Quality Management System (WQMS) is spearheaded in Europe, initially by member countries like Ireland and the United Kingdom, which have now either been converted into Eurocodes or have become redundant. As stated earlier, the newer developments have been built on the basis of these initial attempts to regulate quality and responsibilities of various parties involved. This resulted in the issue of some very detailed guidelines by European partners, which are further adopted by Euro-Norms and International Standards Organization (ISO). The EN 1090 series of specifications is one such document, about which we will discuss a little more in detail further in the section.

There is some understanding whereby all EN specifications are adopted as ISO specifications, but exceptions can be seen. The EN codes and standards that are harmonized are written as EN ISO XXXX, as we will see often written.

The process has evolved wherein the welded fabricated structural product is required to have CE (*Conformité Européenne*) marking; CE could also mean "*Communauté Européenne*" depending on who is interpreting the term. Nonetheless, it is the CE mark that is important; the marking is a symbol of free marketability in the European Economic Area. The CE mark is in fact a conformity mark; the conformity is to the European requirements, meeting the directives related to the design, construction specifications, obligations of contractors, and client's obligations, to assure conformance to product quality. It is now a mandatory requirement for structural fabrication and welding products.

EN IS 1090 is the specification that describes the execution of steel and aluminum structures. It is now a mandatory requirement through EN 1090 that, for any project, the fabrication or Execution Class must be specified. EN 1090-2 describes four Execution Classes, and these classes are graded as being least onerous (class 1) to most onerous (class 4). It is the responsibility of the designer or the party specifying the requirement to determine the execution class required; the specification gives details on how to select the Execution Class. The determination is based on the following variables.

1. Consequence class (CC)

   The objective of consequence classification is to ensure the level of quality required for the structure. There are three CCs, which are three different level of consequences. They are linked with the consequence of the failure of the structure.

   - CC 3 has the most serious consequence, and it includes the high possibility of loss of human life and loss to economy and environment.
   - CC 2 is medium consequence, wherein the loss of human life, social, economic, and environmental consequences is a medium possibility.
   - CC 1 is the least serious consequence to human life, social, economic, and environmental consequence. The possibility is least or minimal.

2. Service Category (SC)

   The service categories are two: SC 1 and SC 2. These are based on the determination of risk from actions of which structure and its parts are likely to be stressed during its installation or use. This would include factors like seismic and/or fatigue strains caused during the process.

- SC 1 covers less-stringent design conditions and is applicable to static and quasistatic structures designed for seismic actions in low seismic zones, and structures designed for fatigue strain caused during lifting and moving by cranes designed to class S_0.
- SC 2 covers more stringent design conditions; it is about the structures designed for fatigue actions and are designed to meet EN 1993 criteria, such as bridges, railroads, road bridges, rotating machinery, cranes designed to meet Class S_1 to S_9, and buildings or structures designed to meet wind- and load-induced vibrations. This category also includes designs that are for more active seismic areas.

3. Product Category (PC)

These are methods to determine the risk from the complexities of fabrication of a structure or components.

- PC 1 applies to components made without welding; if welded, then from steel grade that has a yield strength of 355 MPa or less.
- PC 2 is for lattice structures, welded structures of steel grade of over 355 MPa, components manufactured by hot-forming processes, or any other components deemed very essential for the integrity of the structure.

This uniqueness of quality assurance and CE marking applies to steel products including that of steel plates, beams, welding consumables such as welding wires, and constructed structures like buildings, stadia, and sports arenas.

Thus, the CE marking is the manufacturers' declaration that their product meets the specified characteristics defined as necessary for the product type.

For a manufacturer to be able to use CE marking on its design and product, they are to adhere to certain basic standards of QMS, and that an authorized certified body has to audit and certify their QMS. This process is controlled and guided by EN ISO 3834, and this specification controls the fabrication and certification of welding and welded products.

EN ISO 3834-1 provides criteria to be taken into account for the selection of the appropriate level of quality requirements for fusion welding of metallic materials, among the three levels specified in EN ISO 3834-2, EN ISO 3834-3, and EN ISO 3834-4. It applies to manufacturing, both in workshops and at field installation sites.

EN ISO 3834-1 does not specify requirements for a total QMS. However, QMS elements where their inclusion will complement EN ISO 3834 are defined.

As we understand, welding is a special process; by special, it is meant that it is not possible to make full verification of the weld without destroying it. To examine the mechanical properties, the weld should be cut and a set of samples are drawn to specified requirements and tested. This special condition implies that welding quality is fully dependent on the quality system practiced by the engineering designers, and fabrication and construction contractors.

This is where the application of EN ISO 3834 comes into play, which is to ensure the proper quality of the welded product and optimize the process and product cost. This concept implies that entire welding activity, e.g., from design to erection, must be in strict system compliance from inception to the finished product. To meet these quality requirements of the welding process, the contractor responsible or the fabrication shop should implement, a QMS. The standard EN ISO 3834 sets out the requirements to be met.

There are several steps in a Welding Quality Assurance System (WQAS); to make sure the welding shop has competent welders, there are standardized ways to test the welders. Use of written fabrication and welding procedures (WPS), these welding procedures are to be qualified by testing sample welds made according to the parameters set in the WPS. Once these tests are completed, which can vary from simple to very complex tests, all depend on the Consequence Class (CC), Service Category (SC), Product Category (PC), and risk associated with each and combination of them.

The test data and weld parameters are recorded in a set of documents called welding procedure qualification record (WPQR, or sometimes just PQR). The WPQR explains that, if the parameters recorded in the WPS and its supporting PQRs are followed in production welding, then the weld in most probable case would meet acceptance criteria.

In some production situations, more welders and welding operators may be required than those who welded to qualify the WPS as stated before. In such cases, more welders are required to be qualified.

These welders or welding operators are often qualified according to the same parameters as set in the WPS/PQR. This should, of course, be about the welders' competence, education, and ability to understand and comply with the parameters set for the specific welding procedure (WPS). The welding coordinators are often responsible for the conformance of the product, which includes the correct control over materials, welding processes, welding consumables, and the inspection and testing requirements of the product. All of this, of course, is largely dependent on the welders' education, qualification status, and competence. The welding coordinators' competence requirements, tasks, and responsibilities are regulated in the standard EN ISO 14731, and the fabricator has to declare a "Responsible" Welding Coordinator (RWC), who is effectively accountable for the product satisfying the technical requirements. However, the competence of the RWC is influenced by education, experience, and product knowledge, as well as any independent assessment by a Notified (or Certification) Body, who is required to ensure the correct assessment and effectiveness of both the Management Systems and competence of personnel involved. In this context, the term *Responsible* is used for most of the welding engineering activities of the fabricator. This, in fact, includes at least the following general group of activities.

1. Welding process and equipment
2. Understanding of material and its behavior during welding and associated processes
3. Design and construction
4. Fabrication and application engineering
5. Coordination of welding activities as one well operating machine

These are some of the very basic essentials of producing consistently acceptable quality of welds, and, if implemented correctly, are intended to remove the variations in the quality level and product conformance level.

To ensure the welding process is of good quality, the fabrication shop and the welding contractor need to implement a WQAS.

There are experts, like Weld-Class-Solutions Ltd., in the United Kingdom (www.weld-class-solutions.co.uk), in the field who provide an extremely important service to the industries in training, education, and understanding the concept of WQAS, and as consultants, they also help develop a WQAS specifically suited to the industry.

It may be added that the concept of specific WQAS has become a necessity to conduct business not only in Eurozone but other parts of the world. The adoption of the concept has picked up in several other parts of the world. The author has come across some Canadian engineering consultants demanding the certification of a WQAS through their specifications from their welding and fabrication vendors, and fabrication shops, especially those doing business with Europe, are seeking the help of consultants to develop WQAS for them.

Section 3

Nondestructive Testing

Introduction

1

A welding engineer designs weldments with certain service conditions and performance level to meet the rigors of design conditions. Other than design simulation and possible mathematical modeling, where it is possible, there are only two ways to factually determine if the design will really work. One of the ways is to put every designed product to a real-life test; however, putting weldments to such tests has some very serious implications.

- A real-life test may require huge facilities to test, which will be prohibitive.
- A real-life test may destroy the weldments; for fear of destruction, the weldments may not be tested to full load.

As a result of the limitations of a real-life full load test, the second option is to put the weldments through a testing regime through computer simulations and mathematical modeling. This is complemented with selective tests of the material properties during the production process, which involves inspection of the material and welds using nondestructive testing methods. This would cover most aspects of weldments. In some cases, such as pressure vessels, piping, and pipelines, an additional test of pressure testing is also carried out to prove the design.

The general term *Nondestructive Testing* (NDT), or sometimes *Nondestructive Examination* (NDE), is used to identify all those inspection methods that permit evaluation of material and welds without destroying them.

This section of the book will introduce various nondestructive testing methods, their fundamental principles, and typical application in preconstruction, during construction, and post-construction and integrity management of structures, plants, and equipment.

The common elements in nearly all NDT methods is (a) a source of probing energy, (b) a test specimen appropriate for the energy source being used so that discontinuities may be detected, (c) a capable detector that can accurately measure the distribution and changing energy, (d) a technique for recording or displaying the information received from detector, and (e) a trained and qualified operator to inspect and interpret the feedback from the detector unit.

The fundamental basis of selection of a particular type of NDT method depends on the available energy, the type of material being tested, the objective of inspection, and the degree of accuracy required.

The ability of engineers to take a sound decision to use an NDT method or a group of NDT methods is affected not only by their knowledge of various tests available to the project but also by the knowledge of their limits and advantages over one another, and the engineer's ability to use them to compliment interdisciplinary limitations. Engineers can more effectively design a testing protocol by using their knowledge of primary and secondary manufacturing processes involved in fabrication and production, their sequence, and including of course the sound knowledge of processes

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Table 3-1-1 Identification of various NDT methods.

NDT methods	Name of the test method	Accepted abbreviations
1	Visual Inspection	VT
2	Radiography	RT
3	Magnetic Particle Testing	MT
4	Penetrant Testing	PT
5	Ultrasonic Testing	UT
6	Eddy Current Testing	ET
7	Acoustic Emission Testing	AET
8	Ferrite Testing	FT
9	Leak Testing	LT
10	Proof Testing	PRT

like welding, forging, casting, machining, etc. This will be further aided by in-depth knowledge of heating and cooling cycles used on various materials.

An additional section of case study is included wherein some real-life practical applications of NDT methods are discussed. Typical defects that are encountered in the material after processing or during maintenance and welding or due to corrosion are discussed. The reason why certain NDT methods are more suitable to detect a certain type of defect is also brought out.

We shall discuss the test methods listed in Table 3-1-1 here.

Visual inspection (VT)

2

Visual inspection (VT) is an important part of the quality control system. For several machines, material, and welds, the primary inspection is a VT. This is the simplest form of inspection, sometimes performed consciously as part of a structured inspection program, whereas there are occasions when VT is performed as an unconscious activity as part of day-to-day activity. Sometimes, VT is the only inspection given to material or welds. But most of the time, a VT is the prerequisite inspection method before applying any other test method. In most cases, it works as first line of filtering faulty or defective material and welds.

The inspection of jet engines, upon arrival from flight, involves an extensive regimen of VTs.

Regular inspection of a ship's engine room, decks, and other equipment is a preventive measure to identify and avoid major failures and costly repairs.

Daily, walking around your car before driving is a VT to inspect the tire tread and any other possible damage that might become a cause of serious car damage.

All these are just a few examples of VTs intended to identify, preempt, and prevent possible catastrophic failures. Some of the organized inspection routines have a very structured system with forms and questionnaires to be filled in and responsibilities associated. The others are less structured, but all depend on the associated (potential) seriousness of the resulting accountability of failure in both terms of life and cost.

VT in terms of welding assumes some specialized knowledge, training, and experience. Depending on the end objective of the inspection or the design of the weldments, some demands on the attributes, training, knowledge, and experience of the inspector would differ. The training for an inspector would generally involve classroom education, written examinations, and some real hands-on inspection of welds; such certification is carried out by several national certification bodies like The Welding Institute's http://www.twi.co.uk/ welding inspector certification, American Welding Society http://www.aws.org welding inspector certifications, or The Canadian Welding Bureau http://eng.cwbgroup.org/. These certifying bodies also determine that the inspector has correct vision acuity for distance and color vision. Generally, the ability to read J-1 letters on a Jaeger standard chart at a distance of 12 in. is deemed acceptable near-vision level.

The VT would require that the area to be inspected is fully illuminated so that the inspector is able to see the details of the weldments to be inspected. A minimum illumination of 1000 Lux (100 fc) on the surface is considered an adequate light for VT.

Advantages of visual inspection

The advantage of this test can be following.

1. It is easy to apply.
2. It is quick to apply.

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3. It is relatively inexpensive.
4. Generally, no special equipment is needed.

There is certain physical ability and knowledge expected of an inspector to be efficient in this job.

As stated before, the inspector should have good eyesight and be able to move around and reach difficult-to-reach positions of the material or weld being inspected. The inspector is expected to have good knowledge of the machinery, equipment, and specifications; workmanship standards; and should be familiar with shop practices the inspector is required to inspect.

For conducting an effective VT, the inspector may need the following additional tools.

1. A source of light if natural light is not adequate.
2. Internal inspection of a restricted location can be done with the help of a boroscope, a reflecting glass with added light comes handy in some restricted inspection locations, like a jet engine's turbine blades, corner welds, welds inside a small-bore tubing, etc.
3. A low-powered magnifying glass may be required in some specific cases.
4. Some hand tools and, in some cases, specialized tools of the trade may be required.

Welding inspection assumes a different set of challenges. For inspecting welds, during construction, the following tools may be required.

- Weld profile gauge
- Fillet gauge
- Gap gauge
- Bevel protector
- A ruler, Vernier gauge, or a tape measure of suitable scale

Inspection of welding can be divided in three stages as listed in the following table; the table lists the general inspection scope at all three stages (Table 3-2-1).

Table 3-2-1 The three stages of welding and what to look for at each stage.

Welding inspection stages	Inspection points addressed in these stages
Prior to welding	Is material being welded as per the specification and as per fabrication drawing? Is the joint preparation as per the approved welding procedure and drawing? Clearances, dimensions, backing strips, backing material, or gas filler metal. Alignment, fit-up, distortion control, etc. Verification of WPS/PQRs and cleanliness.
During welding	Welding process and conditions. Filler metal flux or shielding gas. Preheat and interpass temperature and control. Distortion control. Interpass chipping, grinding, gouging, and cleaning. Inspection intervals.

Table 3-2-1 Continued

Welding inspection stages	**Inspection points addressed in these stages**
Postwelding	Dimensional accuracy. Conformity to drawing and specifications. Acceptability with regards to appearances (including weld spatter, roughness, undercuts, overlaps, cracks, open pores, craters etc.). Postweld heat treatment time and temperature. Release for other NDE methods, as applicable.

Table 3-2-2 Weld reinforcement acceptability level.

Material nominal thickness (mm)	**Max reinforcement (mm)**	**Max reinforcement where more stress is expected (mm)**
Less than 2.4	2.4	0.8
Over 2.4 to 4.8	3.2	1.6
Over 4.8 to 13	4.0	2.4
Over 13 to 25	4.8	2.4
Over 25 to 51	5.0	3.2
Over 51 to 76	6.0	4
Over 76 to 102	6.0	6
Over 102 to 127	6.0	6
Over 127	8.0	8

The general acceptance criteria for inspection of a weld profile are given in the Table 3-2-2. It may be noted that various specifications/codes have their own acceptance criteria and would differ significantly from the limits given in the table. One such example is the acceptance criteria for weld in deep-sea steel contrary risers (SCRs), where the acceptable profile may be limited to "ground flush" to parent metal. The alignment given in Table 3-2-2 is similarly stringent, often limited within the range of 0.001–0.004 in.

Radiography

3

Other than the very basic fabrication, most weldments may require more than just visual inspection. The demand of the design may require that health of weld be evaluated in more detail. Such demands may push for additional methods of inspection. Radiography is one of those methods where a two-dimensional picture of three dimensions of weld can be produced, revealing the internal health of the weld.

This nondestructive testing method utilizes radiation to penetrate the material and record images on a variety of recording devices such as film, photosensitive paper, or viewed on florescent screens and various electronic radiation detectors.

The principle of the process is that, when radiation passes through a metal, some of the radiation will be absorbed by dense material, some will be scattered, and some will be transmitted through the less-dense metal; the resultant radiation energy will be varied and recorded accordingly on the viewing media.

For ease of understanding weld inspection, we will focus our discussion on the most common recording medium, film.

The basic process of radiography involves two stages: first is a good readable radiograph and second is the ability to interpret whatever the radiograph presents. The entire process revolves around these two very basic fundamentals. As we delve deeper in the process, the two stages become more technical, limited only by depth of the knowledge the reader wants to dive into.

The requirements to achieve the two basic goals are varied, and sometimes very divergent routes are taken. Table 3-3-1 surmises these essential requirements to accomplish good radiographs. In subsequent paragraphs, each of these are discussed in some detail.

Source of radiation

The heart of radiography is the radiation source. Electromagnetic radiation energy with penetrating properties related to its energy potential or wavelength is unique. Another unique ability of radiation is its ability to ionize elements. These two unique properties are exploited to get good radiographs.

These radiation sources have an extremely short wavelength of about 1/10,000th of light. This enables the source to penetrate the material. The two types of radiation source commonly used for industrial radiography are:

- X-ray machines
- Radioactive isotopes, i.e., gamma rays

For radiographic purposes, both X-ray and gamma ray radiation behave similarly. Both are comprised of the high-energy, short-wavelength portion of the electromagnetic wave spectrum. Throughout the spectrum, X-rays and gamma rays have the same

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Table 3-3-1 Essentials of radiography.

Points	Essentials for taking good radiograph	What is required?
1	A source of radiation	Gamma or X-ray
2	An object to be radiographed	Material or weld
3	Film enclosed in a lightproof holder	Suitable quality of film
4	Producing an exposure in the most advantageous manner	A trained person
5	Processing the film	A chemical processing bath
Points	**Requirement for interpretation of film**	**General requirements**
1	Interpretation	A trained and experienced person

characteristics, and X-rays and gamma rays of the same wavelength have identical properties. These radiation characteristics are listed here.

1. They have no electrical charge and no rest mass.
2. In free space, they travel in straight lines at the velocity of light.
3. They are electromagnetic with energy inversely proportional to their wavelength.
4. They can penetrate matter; the depth of penetration is dependent on the wavelength of the radiation and the nature of the matter being penetrated.
5. They are invisible and incapable of detection by any of the senses.
6. They can ionize matter.
7. They are absorbed by matter. The degree of absorption is a function of the matter density, its thickness, and the wavelength of the radiation.
8. They are scattered by matter; the amount of scatter is a function of matter density and wavelength of radiation.
9. They can expose film by ionization.
10. They can produce fluorescence in certain material.

X-ray

We shall briefly discuss X-ray and how it is generated for industrial applications.

X-ray radiation is obtained from a machine that has a tube consisting of an electron source, a target for the electron to strike, and a means of speeding the electrons in the desired direction.

- Electron Source

  All matter is composed in part of negatively charged electrons. When a suitable material is heated, some of its electrons become agitated and escape the material as free electrons. These free electrons surround the material as an electron cloud. In an X-ray tube, the source of electrons is known as the cathode. A coil of wire called filament is contained in the cathode, and it functions as an electron emitter. When a voltage is applied across the filament, the resultant current flow heats the filament to its electron emission temperatures.

- Electron Target

  X-rays are generated whenever high-velocity electrons collide with any form of matter, whether it be solid, liquid, or gas. Because the atomic number of an element indicates its density, the higher the atomic number of the chosen target material, the greater the efficiency of X-ray generation. The greater the density of the material, the greater the number of X-ray-generating collisions. In practical applications of X-ray generation, a solid material of high atomic number, usually tungsten, serves as the target. As shown in Figure 3-3-1, the target is contained in the X-ray tube on the anode.
- Electron Acceleration

  The electrons emitted at the cathode of an X-ray tube are negatively charged. They are repelled by negatively charged objects and are attracted to positively charged objects. The anode of the X-ray tube is positively charged so it attracts the negatively charged electrons from the cathode, thus free flow of electrons is speeded from cathode to anode.
- Intensity

  The amount of X-rays created by electrons striking the target is one measure of the "intensity" of X-ray beam. Intensity is, therefore, dependent upon the amount of electrons available at the X-ray tube cathode. If all other variables were held constant, an increase in cathode temperature would cause emission of more electrons and increase the intensity of the X-ray beam. To a lesser degree, an increase of positive voltage applied to the anode will increase the beam intensity. Thus, the intensity of the X-ray beam is almost directly proportional to the flow of electron through the tube, and the output rating of an X-ray machine is often expressed in milliamperes of current flow. This "direct proportion" establishes tube current as one of the exposure constants of X-ray radiography.
- Inverse Square Law

  The intensity of an X-ray beam varies inversely with the square of the distance from the radiation source. X-ray-like visible light rays diverge upon the radiation source and cover increasingly large areas as the distance from the source is increased. This is an important law that helps compute radiography exposure and safety procedures. Mathematically, the inverse square law is expressed as:

  $$I_1/I = D^2/D_1^2$$

  where:

  I = X-ray beam intensity at distance D

  I_1 = X-ray beam intensity at distance D_1

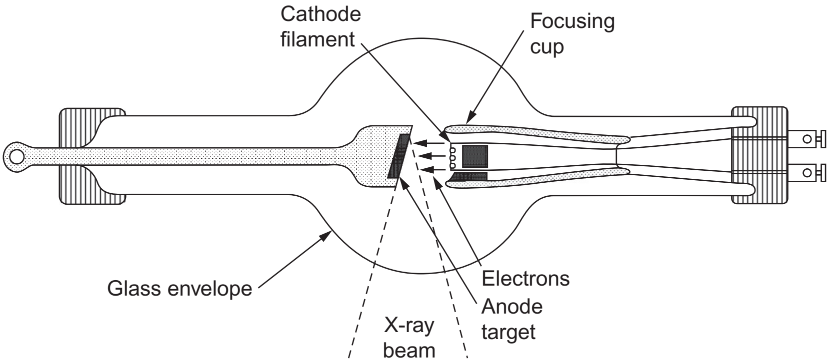

Figure 3-3-1 Typical basic X-ray tube.

- X-ray Quality Characteristics

  Radiation from an X-ray tube consists of previously mentioned characteristics and continuous rays. The characteristic rays are of small energy content and specific wavelengths as determined by the target material. The spectrum of continuous rays covers a wide band of wavelengths and is of generally higher content. The continuous rays are of most use in radiography. Because wavelength of any one X-ray is partially determined by the energy (velocity) of the electron whose collision with the target caused the ray, an increase in applied voltage will produce X-rays of shorter wavelength (more energy). An increase in applied voltage increases the intensity (quality) X-rays. But of more importance to radiography is the generation of higher energy with greater penetration power.

  High-energy rays (short wavelength) X-rays are known as hard X-rays; conversely, low-energy (longer wavelength) X-rays are known as soft X-rays (Table 3-3-2).

To understand the interaction of X-rays with matter, it is necessary to consider the properties of matter that make this interaction possible. Matter is composed of number of tiny particles called atoms. The substances fully composed of identical atoms are called elements, and substances composed of two or more elements are called compounds. Atoms are composed of further small particles listed and defined in Table 3-3-3.

Scatter radiation

In passing through matter, X-rays lose energy to atoms by three ionization processes.

1. Photoelectric absorption
2. Compton scattering
3. Pair production

Table 3-3-2 Effect of Kv and MA.

	Low MA	High MA
Low Kv	Low-intensity soft X-rays	High-intensity soft X-rays
High Kv	Low-intensity hard X-rays	High-intensity hard X-rays

Kv, kilovolts; *MA*, millimeteramperes.

Table 3-3-3 Fundamental particles.

Particle	Description
Proton	A particle carrying a unit positive electrical charge. Its mass is approximately 1 atomic mass unit.
Neutron	A particle, electrically neutral. It has approximately the same mass as the proton.
Electron	A particle carrying a unit negative charge. Its mass is 1/1840 atomic mass unit.[a]
Positron	A particle carrying a unit positive electrical charge. Its mass is the same as an electron.

[a] The atomic mass unit (AMU) is 1/12 the mass of the carbon-12 atom.

All three processes liberate electrons that move with different velocities in various directions. As we know, X-rays are generated when free electrons collide with matter; it follows that these X-rays passing through matter cause the generation of secondary X-rays. These secondary X-rays are minor components of what is called scatter radiation.

The major components of a scatter are the low-energy rays represented by photons weakened in the Compton scatter process. Scatter radiation is of uniformly low-level-energy content and of random direction.

In radiography, the scatter occurs in three manners: internal, side, and backscatter. The following paragraphs discuss the eradiation scatters. Figure 3-3-2 demonstrates the practical aspect of eradiation scatter as it affects the quality of radiographs.

Internal scatter is the scattering that occurs from within the specimen being radiographed. It is reasonably uniform throughout the specimen of one thickness; it blurs the image and reduces the definition of the image. The loss of definition is generally around the edges, and any sharp corners like a bored-hole, step-downs, groves, and recesses cut the specimen.

Side scatter is the scattering from walls of the objects within the vicinity of the specimen or from portions of the specimen itself that causes the rays to re-enter the specimen. Side scatter also blurs and obscures the definition of the edges.

Backscatter as name suggests is the scattering of rays from surfaces or objects beneath or behind the specimen. Backscatter has similar effect on edges of the specimen as internal or side scatter.

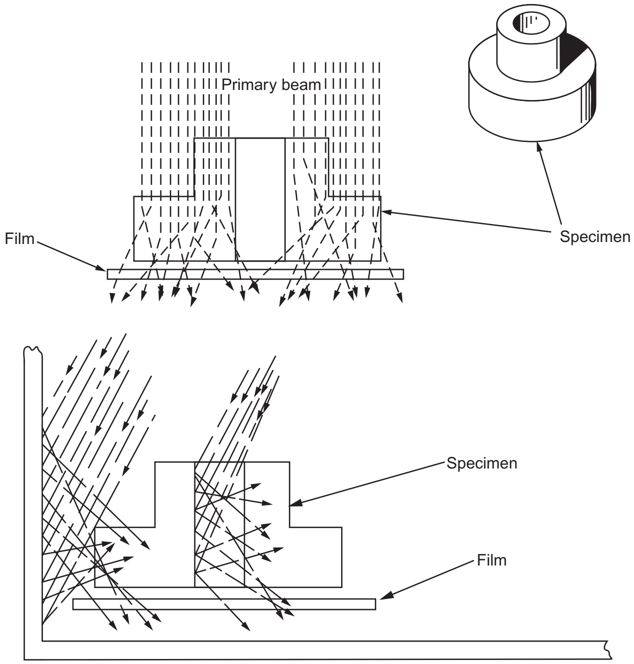

Figure 3-3-2 Radiation scatter.

X-ray equipment

These machines are available in a variety of ranges. They range from as low as 50 kV to up to 30 MeV output capacity. General concept of these machines are discussed in the following paragraphs to bring out a basic understanding of them.

These machines require electrical energy to produce the required radiation; because of this, their portability is limited. The portability is also affected as a typical X-ray tube consists of the following components, making it bulkier and not an easily movable machine. An X-ray machine consists of following parts.

1. Tube envelope
2. Filament heating
3. Anode
4. Focal point

The design of modern X-ray equipment is a result of refinements in the design and meeting the industry requirements. All the earlier discussed parts of an X-ray machine are depicted in Figure 3-3-1.

It is important to take note of these radiographic terminologies, which would be repeated as we discuss the quality of radiographs further in this chapter.

Focal spot: The sharpness of a radiograph is particularly dependent on the size of the radiation source, also called a focal spot. The electron beam in most X-ray tubes is focused so that a rectangular area of the target is bombarded by the beam. The anode target is set at an angle, and the projected size of the bombardment area received by the specimen is smaller than the actual focal spot. The projected area of the electron beam is the effective focal spot. This property allows the reduction of the focal spot as desired; in theory, the limit of reduction is unrestrained and often called a pinpoint reduction. However, in practice, the size of the focal spot is limited by the generation of heat that can destroy the target.

Power sources

Transformers are often the source of electric power; they are various types of iron-core transformers to produce high voltages of up to 400 kvp. They produce self-rectified circuits of half-wave or full-wave rectification, voltage doublers, and constant-potential. They may be mounted in tube head tank units or separately housed.

Resonant transformers often range from 250 to 4000 kvp. These transformers produce high voltage from low input. This type of transformer allows for more compact design as the X-ray tube can be mounted in the central axis of the transformer.

Electrostatic generators operate in the range of 500–6000 kvp. Two motor-driven pulleys drive a (nonconducting) charging belt. Electrons from the charging point pass to the belt and are transferred to the corona cap at the corona point. The accumulated high voltage from the corona cap helps accelerate the beam of electrons emitted by the filament. The equipotential plates distribute high voltage evenly along the length of the tube. The generator is enclosed in a pressurized gas tight chamber to minimize high-voltage leakage.

Linear accelerators utilize radiofrequency energy in a tuned waveguide to produce an induced field, which is directly related to the length of the waveguide section and the radiofrequency. The selection of waveguide lengths and use of a known-frequency electron injected into the guide are accelerated toward the target by the action of the constantly changing induction field.

This should accelerate the electrons to velocities reaching the speed of light that would produce extremely short-wavelength and high-frequency X-rays, but at least at this level of application there is a disconnect in the theory and practice of this process. In practical life, the length of the linear accelerator required to obtain electron velocities equivalent to those used in industrial radiography is about 6 ft.

Betatron accelerators use magnetic circular induction to accelerate electrons. It is basically based on the transformer principles. Alternating current is applied to the primary coil to produce strong variation in the magnetic field in the core of the secondary. The magnets strengthen the magnetic field. X-rays of extremely short wavelength and great penetration power are produced.

Control panel

The control panels of X-ray machines are designed to allow operators to control generation of X-rays to produce exposures. It also serves as a protective layer from damage to the equipment.

As we have seen, there are various types of equipment, and therefore the specific control panel will differ, but a general overview can be made by knowing the different components of a typical panel. Note that some of the features discussed may be differently arranged or may not be part of a specific machine, as they all differ in design and use.

1. Line voltage selector switch. Permits equipment operators to connect to different input sources.
2. Line voltage control. Permits adjustment of line voltage to exact values.
3. Line voltage meter. A voltmeter indicating the line voltage use in conjunction with the line-voltage control.
4. High-voltage meter. Permits adjustment of voltage applied across the tube.
5. High-voltage meter. A voltmeter, generally calibrated in kilovolts, used in conjunction with the high-voltage control.
6. Tube-current control. Permits adjustment of tube current to exact values.
7. Tube-current meter. An ammeter, usually calibrated in milliamperes, used in conjunction with tube-current control.
8. Exposure time. A synchronous timing device used to time exposures.
9. Power ON-OFF switch. Controls the application of power to the equipment. It usually applies power to the tube filament only.
10. Power ON indicator light. Visual indication that the equipment is energized.
11. High-voltage ON-OFF Switch. Controls the application of power to the tube anode.
12. High-voltage ON indicator light. Visual display of the equipment being fully energized and X-rays are being generated.
13. Cooling ON indicator light. Visual indication that the cooling system is functioning.
14. Focal-spot selector control. Used with tubes having two focal spots; permits selection of desired size of focal spot.

Gamma ray

Gamma rays are produced by the nuclei of isotopes undergoing disintegration because of their basic instability. Isotopes are varieties of the same chemical elements but have different atomic weights. A parent element and its isotopes both have an identical number of protons in their nuclei but a different number of neutrons. Among the known elements, there are more than 800 isotopes; of these, about 500 are radioactive. The wavelength and intensity of gamma waves are determined by the source isotopes' characteristics and cannot be controlled or changed.

Every element with an atomic number greater than 82 has a nucleus that has potential to disintegrate because of its inherent instability. Radium is the best known of such elements; it is used as a natural radioactive source. Radium and its daughter products release energy in the form of alpha rays (α rays). Helium nuclei, consisting of two protons and two neutrons with a double-positive charge, release beta rays (β rays), which are negatively charged particles with mass and charge equal in magnitude to those of electrons, and gamma rays (γ rays), which have short wavelength electromagnetic radiation of nuclear origin.

Both alpha and beta particles exhibit relatively negligible penetrating powers. Hence, it is the gamma rays (γ rays) that are of use for radiographers.

Artificial sources

Availability of artificial radiation sources has made radiography much easier. The earliest use as radiation source was radium. There are two sources to obtain a manmade radioactive source. The first option is by an atomic reactor operation involving fission of Uranium-235 that produces several isotopes useable as a radiation source. Cesium-137 is a by-product of nuclear fission.

The second option is the creation of isotopes by bombarding certain elements with neutrons; in this process, the nuclei of the bombarded element is made unstable or radioactive as they capture neutrons. In this group are the isotopes of Cobalt-60, Thulium-170, and Iridium-192. The numerical designators denote its mass number and distinguishes it from the parent isotope or other isotopes of the same element. The artificial products (isotopes) emit alpha rays (α rays), beta rays (β rays), and gamma rays (γ rays) similar to the natural isotopes.

Gamma ray intensity is measured in roentgens per hour at 1-foot (rhf) distance. This is a measure of radiation emission over a given period of time at a fixed distance. The activity of a gamma ray source determines the intensity of its radiation. The activity of artificial radioisotope source is determined by effectiveness of the neutron bombardment that created the isotopes. The measure of activity is the curie, i.e., 3.7×10^{10} disintegrations per second.

Specific activity of a gamma ray source is defined as the degree of concentration of radioactive material within a source. It is expressed in curies per gram or curies per cubic centimeter. Two isotopes sources of the same material with the same activity and different specific activity will have different dimensions. The source with greater specific activity will be the smaller of the two.

The specific activity is an important measure for radiography. It is established that the smaller source results in greater sharpness of the image on the film. This is brought out in Figure 3-3-3, where the size of the source is one factor of the quality of the radiograph.

Half-life:

Half-life is the amount of time required for an isotope to disintegrate (decay) to one-half of its initial strength. It is specific to the isotope element it comes from. This information is useful as a measure of activity in relation with time. A dated decay curve of each isotope is provided on procurement with radioisotope source.

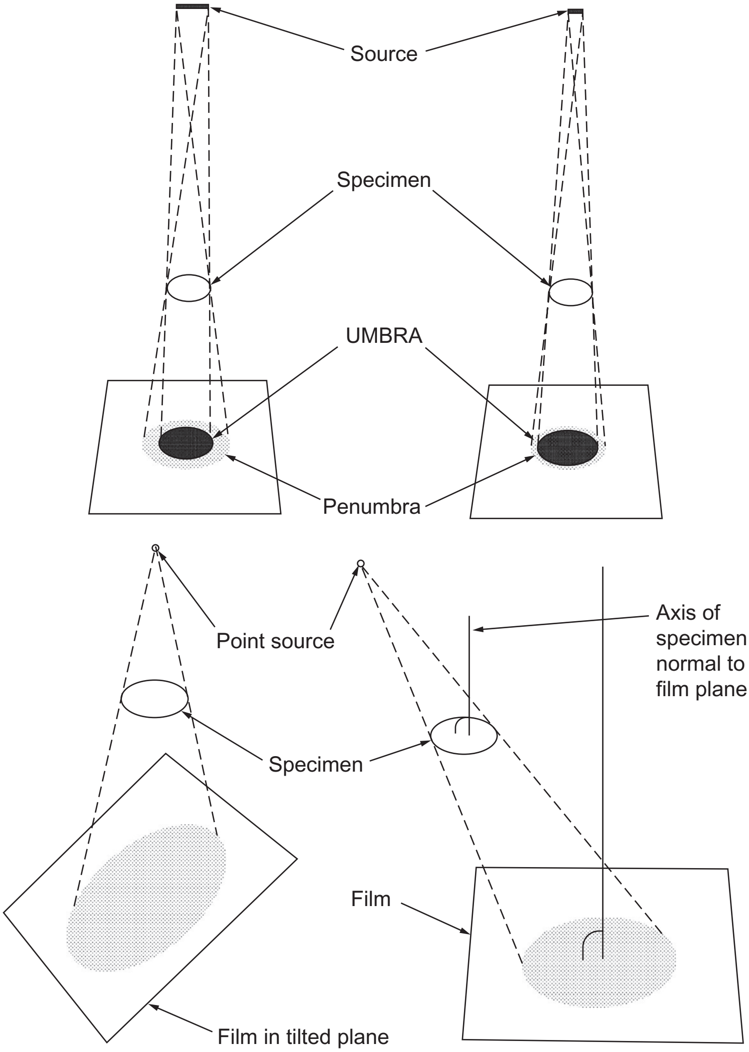

Figure 3-3-3 Penumbra, image sharpness, and distortions.

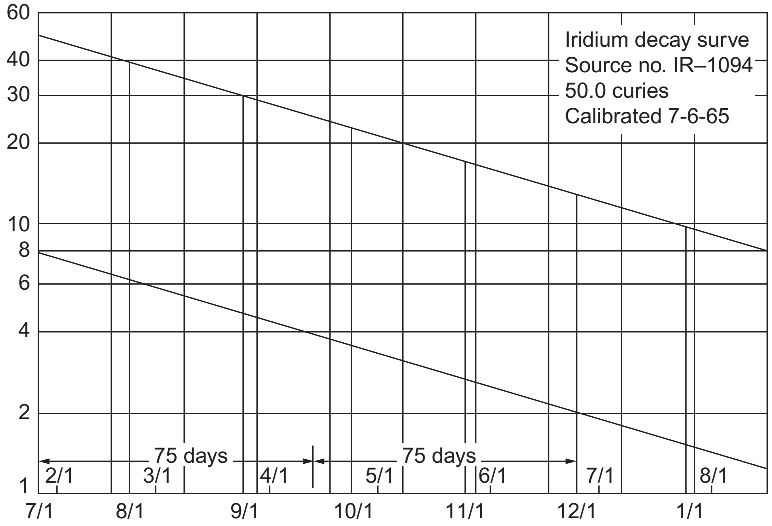

Figure 3-3-4 Typical gamma ray source decay curve.

Table 3-3-4 Isotope characteristics.

Isotope	**Cobalt-60**	**Iridium-192**	**Thulium-170**	**Cesium-137**
Half life	5.3 years	75 days	130 days	30 years
Chemical form	Co	Ir	Tm_2O_3	CsCI
Dose rate at 1 ft per curie	14.4 (r/h)	5.9 (r/h)	0.032* (r/h)	4.2 (r/h)
Practical sources				
Curies	20	50	50	75
RHM	27	27	0.1	30
Approx. diameter	3 mm	3 mm	3 mm	10 mm

A typical decay chart of Iridium 192 is shown in Figure 3-3-4. Table 3-3-4 gives the characteristics of isotopes; it includes the “half-life,” dose rate in curie/foot/hour, and other safety-related information.

The Inverse Square Law states that “intensity of X-ray varies inversely with square of distance from the radiation source,” which is also applicable to gamma rays. The Inverse Square Law is discussed in earlier paragraphs when describing X-rays.

Radiation from a gamma ray source consists of rays with a wavelength (energy) dependent on the nature of the source. Each of the commonly used radioisotopes has a specific use due to their fixed gamma ray energy characteristics.

Table 3-3-5 gives a list of industrial isotopes and the gamma ray energy each of them emits.

Table 3-3-5 Gamma ray energy.

Isotope	Gamma ray energy (MEV)
Cobalt-60	1.33, 1.77
Iridium-192	0.31, 0.47, 0.60
Thulium-170	0.084, 0.052
Cesium-137	0.66

Film

The image capturing is another important aspect of radiography. The most common method is capturing images on film. Radiographic film consists of a thin, transparent, plastic sheet coated on one or both sides with an emulsion of gelatin approximately 0.001-in. thick that has very fine grains of silver bromide. When this film is exposed to X-rays, gamma rays, or visible light rays, the silver bromide crystals undergo a reaction that makes them more susceptible to the chemical process (called developing) that converts them to black metallic silver. In other words, exposure to radiation creates a latent image on the film, and further chemical processing makes the image visible.

Usefulness of any radiograph depends on its effect on human eyes. A good interpretation depends on the contrast and definition detectable by the eye. When a radiograph is viewed for interpretation, the details of the image should be clear and understandable. That would depend on the amount of the light passing through the processed film. The areas of high density appearing as dark gray will be viewed against an area of light density appearing in various shades of light gray. The density difference of the two is called contrast of the film. The other attributes that affect the quality of film are sharpness of the film image, also called definition of the film.

More about film is discussed in the paragraphs discussing the quality of radiographs.

There are several factors that contribute to the successful radiographs being taken, including the geometry of the object being radiographed, quality of film, the exposure time, and processing and viewing conditions.

Radiographic exposure techniques

Radiography is carried out based on the geometrical shape of the material and the required details of the image. Best possible configuration is chosen, and the process of film placement and location of radiation source is determined. In this respect, the configuration of cylindrical objects like pipelines and offshore structural members is more critical. The radiographer must ask the following questions and, based on the answers, consider the best possible exposure technique to use.

- Which arrangement will provide optimum image quality and area of interest (weld) coverage?
- Which arrangement will provide the best view for those discontinuities most likely to be present within the material and the area of interest?

- Will a multiple film exposure technique be required for full coverage?
- Can a panoramic-type exposure be used?
- Which arrangement will require the least amount of exposure time?
- Can the exposure be made safely?

There are various exposure techniques used to produce best possible image. Figure 3-3-5 shows typical exposure arrangements. We will discuss a few of the most common techniques in the following paragraphs; these technologies are very common in most of plate and tubular construction, including piping, pressure vessels, boilers, and structural fabrications and pipelines.

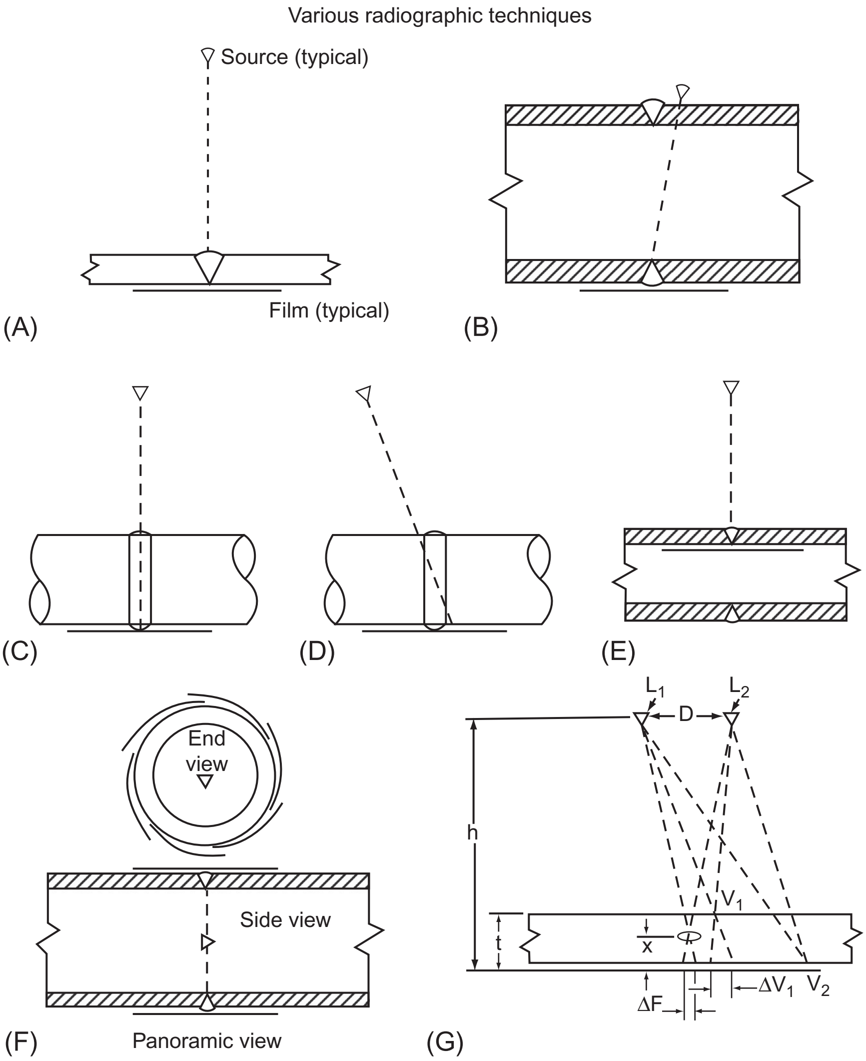

Figure 3-3-5 Radiographic techniques.

Single-wall single-image (SWSI)

On a plate (sketch A), the arrangement is simplest. It has good exposure geometry, and proper positioning of radiographic tools is possible. It is the most practical setup. The figure shows a plate butt-weld (object) and a film placed below it. The radiation source is placed opposite of the film, keeping the object between the film and the source.

Exposure E is a similar arrangement in a pipe; the film is placed in the pipe close to the weld. The source is outside the pipe at a distance from the pipe to make a good exposure. Both these techniques are examples of single-wall single-image (SWSI) viewing.

Panoramic technique

Sketch F describes the panoramic viewing technique. This is another variant of the SWSI technique. The technique is used for cylindrical objects of relatively large diameter greater than 90 mm (3.5 in.) nominal diameter. The film(s) are placed on the outer surface close to the weld (material), and a source is placed in the pipe so that it sits in the center of the pipe allowing radiation to travel an equal distance to all parts of the pipe's circular cross-section. This allows the full girth of the pipe to be exposed all at the same time.

All these techniques produce a film that has radiation penetrate through a single wall of the material, producing the simplest image of the weld on the film.

Double-wall single-image (DWSI)

As contrasted with the earlier described SWSI technique, in sketch B, the radiation source is positioned on the outside of the pipe wall with film placed on opposite side. In this setup, the first wall closest to the source is considered nonexistent, and the source is offset. This is a double-wall single-image (DWSI) viewing technique.

Double-wall double-image (DWDI)

When the pipe diameter is relatively small, less than nominal diameter of 38 mm (1.5 in.), then the entire circumferential weld is exposed straight through both walls, as shown in sketch C. Image of both walls is projected onto the same film area. The determination of defect location and depth is difficult in this DWSI viewing. However, if the wall thickness and the diameter permit the source to be offset to obtain an elliptical image of the weld as shown in sketch D, an experienced interpreter will be able make best judgment of the type and location of any discontinuity viewed in the film.

Radiography presents a two-dimensional image of the object. It is not possible to determine the depth of any discontinuity. To meet this challenge, a technique is used with two exposures; see sketch G. These two exposures are taken in the same setup, on two films with an offset (D) in the location of the source, maintaining the focus to film distance (h) as a constant. The resulting films provide parallax to reveal the third dimension. With fixed-lead markers V_1 and V_2 on source and film side, the shadow of flaw (F) and marker V_1 will change position to ΔF and ΔV_1. If the thickness of the material being tested is t, then the distance of the flaw above the film is calculated as:

$$\text{Distance of the flaw from film } (X) = t * \Delta F/\Delta V_1$$

It is important to note that this calculation assumes that the image of the bottom marker V_2 remains essentially stationary with respect to the film. This may not always be possible, for example, if the film cassette or film holder is not in contact with the bottom surface of the test object or a larger source shift is used. In these instances, the location of the flaw may be computed by the following formula:

$$\text{Distance of the flaw from film } (X) = h * \Delta F/D + \Delta F$$

where:

X = Distance of flaw above film
h = Focus to film distance
ΔF = Change of position of flaw image
D = Distance source has shifted from L_1 to L_2

Radiographic image quality

Practical radiography is a relatively simple process, but it involves a large number of variables and requires well-organized techniques to obtain consistent quality. The radiographic image must provide useful information regarding the internal soundness of the specimen. Image quality is governed by two categories of variables that control:

1. Radiographic contrast
2. Radiographic definition

Both these general categories can be further divided. We shall briefly discuss them here.

Radiographic contrast

In a radiograph of a material that has varying thickness, there is different absorption of radiation. This results in different film densities; the thicker sections appear lighter than the thinner sections on the film. This difference in the darkness of the film from one area to another is called "radiographic contrast." Any shadow or details within the image is visible by means of the contrast between it and the background images. It may be noted that, up to a certain degree, the greater the degree of contrast or density differences in the radiograph, the more readily various images will stand out. The radiographic contrast of concern here is the result of a combination of two additional contrast components, the subject contrast and film contrast.

Subject contrast

Subject contrast is caused by the range of absorption of radiation by the subject, i.e., the material being radiographed. This is affected by (a) the mass of the subject, including the atomic number and the thickness, and (b) the penetrating power of the radiation source, which is the wavelength of the radiation used. The subject contrast is also affected by scattering of the radiation. We have discussed types of radiation scatter earlier in this chapter.

Film contrast

Film contrast is caused by the characteristic variables of the film used to record the image. Recording process, depending upon the film type and related variables, can amplify the difference in film densities created by subject contrast. This is called "process contrast amplification." Film emulsion is manufactured to render different degrees of film contrast. They can also affect the speed of the film and level of graininess of the film.

The principles of film contrast are best understood by the film characteristic curve, also called H&D curve, named after Hurter and Driffield who devised the characteristic curve (Figure 3-3-6).

The curve relates to the degree of darkness (density) to the logarithm of radiation exposure. The radiation exposure (R) of the film is defined as the product of the radiation intensity (I) exposing the film and the time (t) of exposure duration. The relationship is expressed as:

$$R = I * t \qquad [1]$$

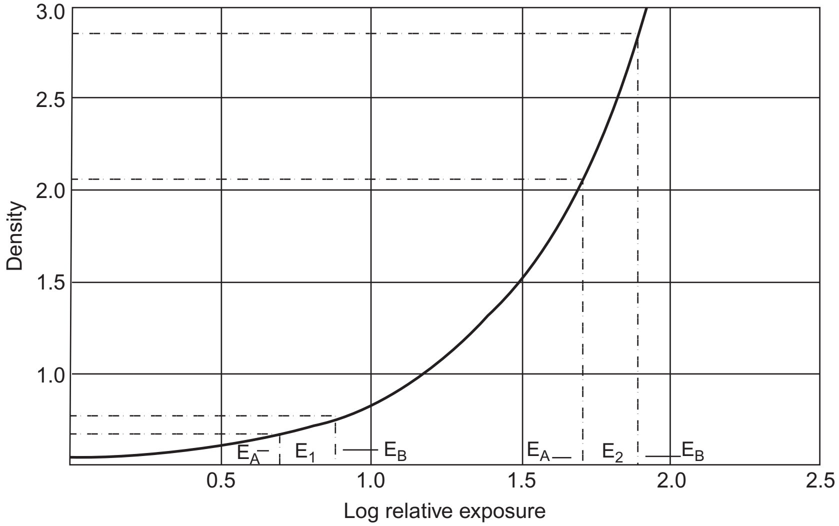

Figure 3-3-6 Film characteristic curve.

The exposure value is expressed as a logarithm (usually base 10) for two reasons: one being the convenience in comparing the otherwise long scale of exposure units, and second is that a change in exposure (ΔR) on a logarithmic scale has a constant spread throughout the scale, whereas the same ΔR would have a wider and wider spread along an arithmetic scale. A constant exposure difference is the basic tool that renders a characteristic curve useful.

Film density (D), or optical transmission density, is defined as:

$$D = \mathrm{Log}_{10}\, I_0/I_t$$

where:

$D =$ Film density
$I_0 =$ Intensity of light incident on film
$I_t =$ Intensity of light transmitted through the film (as seen by the eyes)

A film density of 1.0H&D units means that 1 out of 10 parts of light will reach the eye after being transmitted through the film, or:

$$D = \mathrm{Log}_{10}\, 10\,\text{units}/1\,\text{unit} = 1.0\,\text{H\&D density}$$

The shape (slope) of the curve at any particular film density is not only dependent upon the type of film selected but is also influenced by the degree of development and the type of intensification screens used.

Thus, the shape or the slope of the characteristic curve and density of the film are two factors that define the film contrast.

Radiographic definition

The definition of a radiographic image is as important as the radiographic contrast discussed earlier. The definition concerns the sharpness of the image. "Sharpness" means the degree of abruptness of the transition from one density to another. The more abrupt this transition, the greater the ease in identifying or defining the image. It is easier to discern details in a sharp radiograph than those in an out-of-focus one.

The two components of radiographic definition are exposure geometry and film graininess, and both are briefly discussed next.

Exposure Geometry:

The sharpness aspect of the exposure geometry is shown in Figure 3-3-3; the penumbral shadow is affected by (a) source to film distance, (b) source size, (c) and specimen to film distance.

The source of radiation has physical size. It casts its shadow (penumbral shadow), also called geometric unsharpness, behind the object. This shadow blurs the image. A radiographer cannot change the size of the radiation source, so this is a constant for the field personnel, which is beyond their control. However, increasing the distance between the source to specimen, decreasing the space between film to specimen, or a combination of both, can reduce the effect of penumbral shadow (Table 3-3-6).

Table 3-3-6 Radiation source size.

Source size/focal spot	Typical diameter/area
Gamma ray sources	1.6–13 mm
X-ray	Varies from 6 to 8 mm^2 to a fraction of a square millimeter

The change in exposure conditions related to geometry—focus and projection—are interdependent in their effect upon image sharpness. The object thickness also plays its role; an object that's too thick amplifies the penumbral shadow. If the object under examination is positioned farther from the film for a given source to film distance (SFD), the penumbral shadow will noticeably increase. The variables governing the penumbral shadow or "geometric unsharpness" are mathematically related as following:

$$U_g = FT/D$$

where:

U_g = Geometric unsharpness
F = Focal spot size of the source
T = Specimen thickness
D = Source to specimen distance

The human eye can detect geometric unsharpness (U_g) up to 0.25 mm. Most good radiographs will have U_g less than 1 mm (0.040 in.).

Film Graininess:

Film graininess is the visual appearance of irregularly spaced grains of black metallic silver deposited in the finished radiograph. Radiographic films of all brands possess some degree of graininess. There are four major factors that determine the degree of graininess on a finished radiograph.

1. The type and speed of film
2. The type of screen used
3. The energy of radiation used
4. The degree of development used

Fluorescent intensifying screens produce what is termed "screen mottle". Screen mottle gives an appearance of graininess, considerably softer in outline than film graininess. This is a statistical variation in absorption of radiation quanta by areas of the screen and the resulting fluctuation in intensification.

The energy level of the source usually affects film graininess. Higher energy radiation produces increased graininess. It has been attributed to electron scattering with the emulsion and subsequent sensitization adjacent to the silver halide grains.

Development or processing of exposed radiograph beyond the manufacturer's recommended time and temperatures can cause increased amount of grain clumping leading to a visual impression of film graininess.

Image quality indicator (IQI) or penetrameter

As we have seen through this brief discussion of radiography, there are several variables that come together to give an acceptable level of image quality in the radiographic process. A need is felt to develop a quality assurance tool for consistent results and for acceptable comparison of quality of the image produced by different technicians and use of different films. This tool has to be field applicable. Radiographers use a tool called radiographic image quality indicator (IQI) or penetrameter. Figure 3-3-7 shows images of a typical IQI used; as stated earlier this is also called a penetrameter. Penetrameters are manufactured in standard sizes of plate or wire in incremental thickness. The requirement varies from user to user, but the set of IQIs manufactured cover most of the requirements by overlapping the thickness of material being radiographed. The construction of IQIs is in the material groupings to meet a majority of the materials used in construction. The material is often grouped based on their level of absorption, for example, from Group I for lighter materials to Group V for heavy metals. The IQI material used for the job must be selected from the same group as the specimen to be examined.

The image quality requirement is expressed in terms of the penetrameter thickness or, for wire-type penetrameter, the diameter of the visible wire. Most industrial

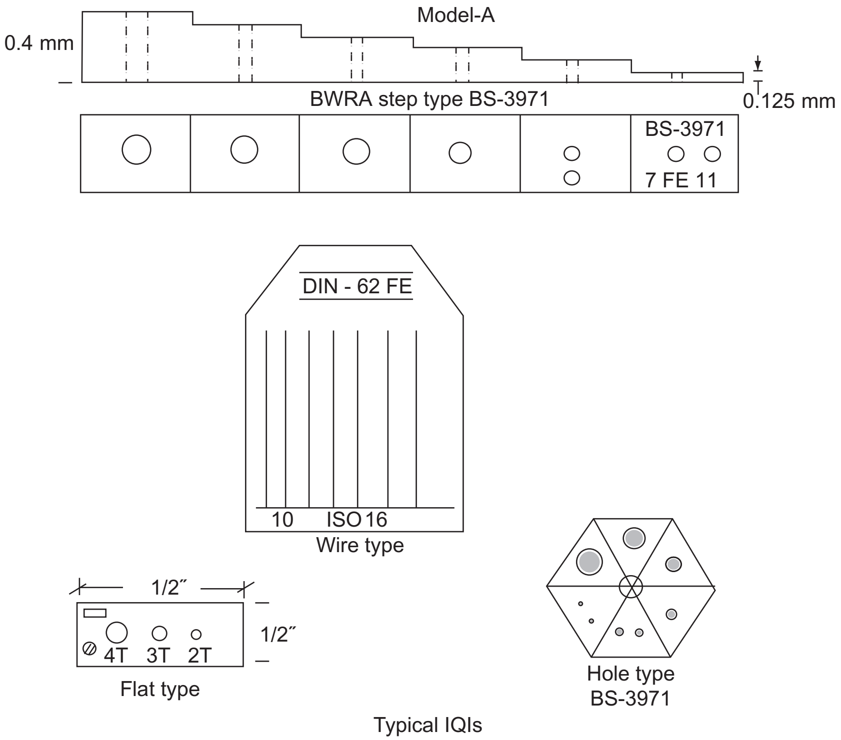

Figure 3-3-7 Typical IQI.

radiography is required to have a sensitivity level of "2-2T." The first 2 requires the penetrameter thickness (wire diameter, in case of wire-type IQI) to be 2% of the specimen thickness. The second part, 2T, together requires that the plate-type IQI hole-size is twice the thickness of the IQI plaque is visible on the radiograph. The sensitivity of a radiograph increases as the number is lowered.

Radiation safety

The effect of radiation on living cells is damaging, and the damaging effect of radiation is dependent upon both the type and the energy of the radiation. For radiation safety, the cumulative effect of radiation on the human body is of primary concern.

The exposure is measured in physical terms, and then a factor is used to compensate for the biological effect of different energies. Let us discuss briefly the various units used to measure radiation exposure.

Roentgen: The roentgen (r) is the unit that measures X-ray and gamma ray radiation in air. Roentgen is a physical measurement of X-ray and gamma-ray (γ-ray) radiation quantity. It is defined as the quantity of radiation that would produce one electrostatic unit (esu) of charge in one cubic centimeter of air at standard pressure and temperature. One roentgen of radiation represents the absorption by ionization of approximately 83 ergs of radiation (energy per gram) of air. In practical use is, however, a unit is called milliroentgen (mr), which is 1/1000 of roentgen.

Rad: Radiation Absorbed Dose (Rad) is a unit of radiation absorbed by humans. It represents absorption of 100 ergs of energy per gram of irradiated material at the place of exposure.

Rbe: Relative Biological Effectiveness (Rbe) is an assigned value to various types of radiation, determined by the radiation's effect on human body. National Committee on Radiation Protection has calculated Rbe values. These values are given in Table 3-3-7.

As can be seen from the table, the calculation of radiation safety level is easy as the unit used is the rem dose. For X-rays and gamma rays, it is a simple calculation as the roentgen dose is equivalent to the rad dose, and the rbe of both X-rays and gamma rays is 1. Thus, a measurement of roentgen dose in effect becomes a measurement of rem dose.

Table 3-3-7 RBE values.

Radiation	**RBE values**
X-ray	1
Gamma ray	1
Beta particles	1
Thermal neutrons	5
Fast neutrons	10
Alpha particles	20

Automization of radiography process

More developments have taken place in automizing radiography techniques with digital viewing of the welds. The reports on DVD have now given way to real-time and remote viewing through the "cloud" and other systems being used by various technology developers. Like any fast-developing technologies and their adaptations, each have their limits and advantages that must be evaluated for the specific use.

Magnetic particle testing

4

Magnetic particle testing is a nondestructive method that detects such discontinuities that are either buried slightly below or open to the material or weld surface. Its advantage over visual inspection is that it can detect defects that are buried below the surface and also surface opening defects that are too small to be visible by naked eye. The sensitivity of the method is dependent on several factors as describe in this chapter.

The process is limited to such materials that have ferromagnetic properties responding to magnetic principles. This implies that this method is not applicable for nonferrous and nonmagnetic material.

Because a wide variety of discontinuities can be located by this method, the training and experience of the tester is of great importance. For example, a person experienced in interpreting castings may not find it easy to interpret defects in welding and/or wrought material; same is true for an experienced weld defect interpreter if asked to interpret a casting.

The process requires some fundamentals to be correctly identified and agreed upon prior to the testing. These are often written or referenced documents called specifications. They address the following essential points.

- Objective of testing
- Identification and description of test object
- Details of the testing techniques to be used
- Acceptance criteria
- Rework and retesting details

This technique is not a substitute for radiography or ultrasonic testing of any material or weld. As stated at the beginning of this section, each nondestructive testing (NDT) process has its advantage and limits. The engineer specifying the test must decide upon the objective of testing and what types of discontinuities are expected. A selection of test method must be made on this basis; it is possible and practical to consider more than one NDT method to capture various types of discontinuities that may be expected in a particular weldment.

Principles of magnetic particle testing

The basic principle of magnetic particle testing is as follows; when a magnetic field is established in a ferromagnetic material containing one or more discontinuities in the path of magnetic flux, minute magnetic poles are set up at the opposite faces of the discontinuities. These poles have stronger attraction for the magnetic particles than the surrounding surface of the material, thus making it clearly visible against the contrasting background or under fluorescence of black light.

The most apparent characteristic of a magnet is its ability to attract any magnetic material placed within its field. This property is attributed to its tendency of line of

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force that passes through the magnetic materials, as they offer a path of lower reluctance than a path through the surrounding atmosphere; these lines of force tend to converge into the magnetic material.

The object of inspection is magnetized either by electromagnet or by a permanent magnet. In a permanent magnet system, the north and south poles are at opposite ends, which is a longitudinal magnetization. These poles produce a flow of imaginary lines of force between them to create a magnetic field in the surrounding material. This is explained by the following experiment with a bar magnet.

If a bar magnet is notched, as shown in Figure 3-4-1, the flux distribution or flow of the lines of force will be markedly changed in the area surrounding the notch. The distortion in the line diminishes as the distance from the breach in the magnetic field increases. In this condition, each face of the notch assumes an opposite polarity, producing a flow of leakage flux across the air gap. It is this leakage flux that permits detection of defects by the magnetic particle method. Irrespective of what method is used to magnetize the test object, the attribute of a magnet remains the principle of the test method.

The electromagnetic method is more often used. In this method, the test object is magnetized by introducing high current or by putting the test object in a current-carrying coil. The magnetic field in the test piece is interrupted by any discontinuities producing a magnetic field leakage on the surface. The area to be inspected is covered by finely divided magnetic particles that react to magnetic field leakage produced by the discontinuity. The magnetic particles form a pattern of indication on the surface as magnetization of these magnetic particles assumes the approximate shape of the discontinuity.

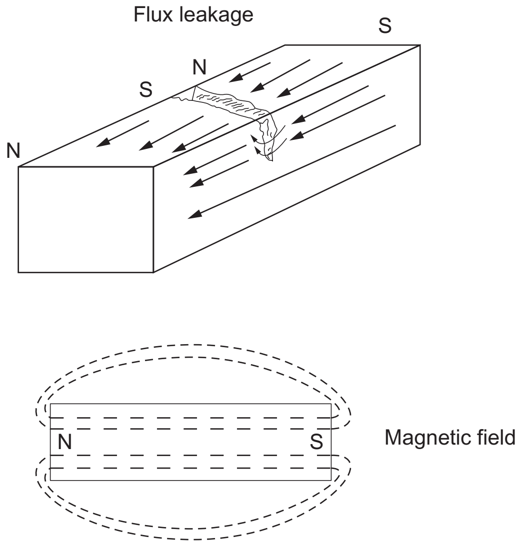

Figure 3-4-1 Magnetic field and flux leakage.

Some of the commonly used methods for magnetizing a test object are based on how the magnetizing field in a given object will be induced and managed to the best advantage. We shall briefly describe them in this chapter.

- Longitudinal magnetizing using coils
- Circular magnetizing using coils
- Magnetizing by use of current carrying conductor
- Prod magnetization

Calculating magnetizing current

The importance of the correct amount of current to be used for testing can never be overemphasized. Just to illustrate the point, two extreme conditions are listed in the following; too small current will produce low magnetic field and will be unable to detect all possible discontinuities; on the other side of the spectrum, too large current may produce too strong magnetic fields that would mask the small and tightly adhering faces of a crack.

Magnetic current should be established by standards, specifications, or given within the purchase order. In the situation where a specification is not available, the current requirement may be calculated as:

1. Longitudinal magnetizing: 3000–10,000 A turn.
2. Overall circular magnetizing: 100–1000 A per in. (or 4–40 A/mm) of the outside diameter of the part.
3. Prod magnetization: 100–125 A per in. (or 4–5 A/mm) of the prod spacing.
   Dry magnetization: Prod spacing of 3–12 in. (75–340 mm).

Wet method: Prod spacing of 2–12 in. (50–340 mm).

Typical longitudinal magnetizing with electromagnetic yoke is shown in Figure 3-4-2.

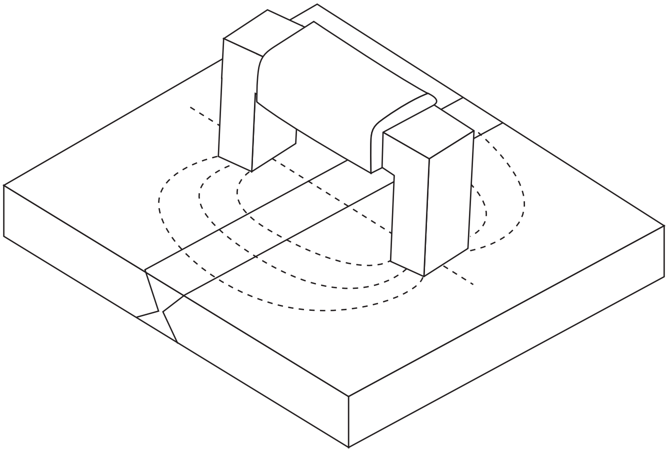

Figure 3-4-2 Longitudinal magnetic field developed by electromagnet.

Type of magnetizing current

High-ampere low-voltage current is commonly used for testing. Alternating current (AC), direct current (DC), and rectified current are used for testing. Most of the portable equipment used for field-testing either use permanent magnets or electromagnets, but these have limitations. They are capable of detecting surface-opening defects, but they are not very efficient in detecting subsurface defects.

AC is used where subsurface evaluation is not required, as only the surface of the test material is magnetized. This method is effective for locating surface-opening discontinuities.

DC magnetization produces a field that penetrates throughout the part; as a result, it is more sensitive in detecting subsurface discontinuities. A three-phase full-wave rectified current produces results comparable to the results obtained by battery-powered magnetization.

Half-wave rectified single-phase current provides maximum sensitivity. The pulsating field increases particle mobility and enables the particles to line up more readily in weak leakage fields. The pulse peaks also produce a higher magnetization force.

Inspection method

There is a specified sequence of operation for a successful test process. These are listed as follows.

1.	Precleaning of the test surface	
2.	Application of the current	Continuous or residual application
3.	Application of inspection media	Dry, wet, color contrast, florescent, etc.
4.	Inspection method and evaluation	Use of visual aids, including ultraviolet (black) light
5.	Demagnetizing	Residual magnetism
6.	Reporting	

Precleaning of Test Surface

The surface preparation is very important for obtaining satisfactory results of testing.

The condition of the surface is an important variable to obtain good results from the testing. The material to be tested may be in as-welded, as-rolled, as-cast, or as-forged condition. The test surface of the material may contain various process contaminates that may mask the test result or mislead the interpretation of the test. Hence, the surfaces of the parts to be tested are prepared by grinding, machining, solvent or water cleaning, or other methods that are not capable of blocking the surface opening of the possible discontinuities.

Prior to the magnetic particle examination, an area about 100 mm around the actual test areas on the surface are visually examined to ensure that the material is dry and free of all dirt, grease, lint, scale, welding flux, weld spatter, paint, oil, and other extraneous matter that could obscure surface openings or otherwise interfere with the examination.

Drying after preparation

Surfaces to be examined are dried after cleaning. Drying is done by normal evaporation or by blowing with forced hot or cold ambient (≈20°C) air. It must be ensured that the cleaning solution has evaporated prior to application of the magnetizing current and magnetic particles.

Application of the current

High-amperage, low-voltage current is usually used, but AC, DC, or rectified current can be used for magnetizing the parts to be inspected.

Portable equipment that makes use of an electromagnet and sometime permanent magnets are also used. Both these methods are able to detect only surface cracks.

Alternating current

When an alternator produces AC voltage, the voltage switches polarity over time in a very particular manner. If this polarity wave trace is graphed over time, it is seen as changing rapidly but in a smooth transition over the crossover line (point zero). The shape of the curve so-produced is called a sine wave.

One cycle of this reversal is termed a wave cycle, the rate of this alternating is called frequency, and it is measured in Hertz (Hz). In the United States, the electrical supply from the grids is at 60 Hz, whereas, in most of the Europe, the frequency is at 50 Hz.

Due to the sine wave, the penetration of the current to magnetize the material is only surface-deep, thus only the surface of the metal is magnetized by AC. The method is effective for locating discontinuities that extend to the surface, such as fatigue or service cracks. Similarly, in a weld, the surface opening can be detected by AC current magnetizing. As stated in the introduction, this type of magnetizing is not able detect subsurface discontinuities.

Direct current

Unlike AC current, the wave of travel in DC is linear and flat. Due to this, the DC magnetizing of metals is able to penetrate through the material; hence it is more sensitive compared with AC magnetizing for detection of subsurface discontinuities.

Full-wave, three-phase, rectified current produces results essentially comparable to DC obtained from batteries.

Half-wave, single-phase, rectified current provides maximum sensitivity. The pulsating field increases particle mobility and enables the particles to line up more readily in weak leakage fields. The pulse peaks also produce a higher magnetizing force.

Operational sequence of magnetizing and application of the inspection medium has an important bearing on the sensitivity of the method.

Continuous or residual application of current

Continuous method is the process in which the magnetizing and application of dry magnetic powder is simultaneous. In fact, the application of media (dry powder) is done only as the current is flowing in the test material.

This condition offers maximum sensitivity, as the magnetic field is at its peak during the entire process. If the current is stopped during the application of media, only the residual current will be able to hold the indications.

If wet suspension is used along with the continuous method, the media suspended in wet suspension is allowed to flow over the material as the magnetizing current is applied. The inspection is carried out as the media is applied, and current is applied in a burst of about one-half second.

Residual method, as the name implies, depends on the residual magnetic field to detect discontinuities. The current is applied, magnetic fields developed, and then the current is switched off as the indicating media is applied. The accuracy and sensitivity is dependent on the strength of the residual magnetic field. It is obvious that the application of this method is most effective on materials that have higher magnetic retentivity.

The knowledge of magnetic permeability and retentivity of material being magnetized and/or tested will help establish the best method for magnetizing and testing. If available, the hysteresis curve of a particular metal must be reviewed. This will help develop an effective magnetizing or demagnetizing procedure.

A hysteresis curve is a plot of flux density versus magnetic force. A hysteresis curve could be either a wide-loop curve or a slender-loop curve, as they both signify specific properties of the magnet. The following are the typical characteristics of hysteresis curve.

A wide-loop curve signifies:

- Low permeability of the metal being magnetized
- High magnetic retentivity of magnetized material
- High coercive force required to remove magnetism from the material
- High reluctance (difficult to magnetize)
- High residual magnetism

A slender-loop curve signifies:

- High permeability of the metal being magnetized
- Low magnetic retentivity of magnetizing material
- Low coercive force required to remove magnetism from the material
- Low reluctance (easy to magnetize)
- Low residual magnetism

Dry method of inspection

The method, as the name suggests, is based on the use of dry powder media for inspection. The method uses finely divided ferromagnetic particles in dry powder form. The particles are coated to allow for greater mobility. These particles are uniformly dusted over the inspection surface. Dusting bags, atomizers, or spray guns are used for dusting. These particles are given a variety of colors to easily distinguish the formed patterns against the background while inspecting.

Wet method of inspection

In the wet magnetic particle inspection method, the material to be inspected can be sprayed, flowed, or immersed in a bath of the suspension. The method is used both as color contrast and fluorescence under an ultraviolet (black) light.

The size of particles used for the wet method is smaller compared with dry powder. This is because the particles are suspended in a liquid bath of light petroleum distillate. These particles are either in dry concentrate form or a paste from; the final formulation for use is prepared either with oil or with a water bath. These are specific formulations and generally cannot be interchanged from oil base to water base. The smaller size of the particles makes the wet method more sensitive to fine surface defects, but it is limited in detecting subsurface defects. When a bath method is used, it is to be continuously agitated to prevent settling of particles. The water-based suspension has an advantage, as it is as sensitive as an oil-based suspension but is not a fire hazard like flammable liquids such as kerosene oil, which is often the base for the magnetic particle bath.

Viewing conditions

The viewing conditions for nonfluorescent wet-particle testing requires that the parts being inspected are illuminated to at least 200 fc (2152 Lux) of visible light.

When using fluorescent material, it is necessary that ultraviolet light, also called black light, is used to view indications presented by fluorescent particles.

Inspection under ultraviolet (black) light

Ultraviolet light supplies the correct wavelengths to cause florescent material to fluoresce. The equipment essentially consists of a regulating transformer, a mercury arc lamp, and a filter. The mercury arc bulb and the filter are contained in the reflector lamp housing, and the transformer is housed separately. A deep red-purple filter is designed to pass only those wavelengths of light that will activate the fluorescent material.

For correct test results, the lamp should be able to produce an intensity of minimum 800 $\mu W/cm^2$ (microwatts per centimeter square) in a 3-in. circle at 15-in. distance.

Once the switch is turned on, it takes about 5 min for the light to attain full intensity. Once turned on, the light is kept “ON” for the entire duration of the testing to keep the light ready for inspection without interruptions, and also because frequent switching ON and OFF shortens the life of the arc bulb.

The dust and dirt sticking on the filter glass significantly reduce the intensity of the light. This requires that the filter glass is always kept clean.

Penetrant testing

5

The basic principle of liquid penetrant testing (PT) is based on capillary action. The capillary action allows the penetrant to enter the opening of the defects, remain in when the liquid is removed from the material surface, and emerge on the surface upon application of a developer, similar to the capillary action of a blotting paper. If done properly, it is a very effective test method that would expose surface-opening discontinuities for visual inspection. Inspection can be carried out either without any addition visual aid or, if florescent penetrant is used, under ultraviolet black light. The process is excellent for nonmagnetic material. Very small and tight imperfections can be easily detected.

The method has several variants divided into two basic categories: (a) fluorescent and (b) visible dye method, each having their advantages; we shall discuss them further in this section.

General procedure

Liquid penetrant examination is performed in accordance with a written procedure. The procedure is written, keeping in mind the job-specific requirements and considering the following details.

- The objective of the examination.
- The shapes and size of the material to be examined and the extent of the examination.
- The type of each penetrant, penetrant remover, emulsifier, and developer to be used; these are specifically identified with product-specific number or letter designators.
- Details of processing of each stage are included, for example, for preexamination cleaning and drying, the dwell time, application method and temperature range, cleaning materials to be used, and minimum time allowed for drying.
- The processing details for removing excess penetrant from the surface and for drying the surface before applying the developer.
- The processing details for applying the developer and length of developing time before interpretation.
- The processing details for postexamination cleaning.

Any change in part processing that can close surface openings of discontinuities or leave interfering deposits, such as the use of grit blast cleaning or acid treatments, must be identified and remedial action must be suggested.

Penetrant materials

In general, the term *penetrant materials* includes all penetrates, solvents, or cleaning agents that are used in this examination process. Penetrant material has the capacity to enter the crevices opening on the surface of the material. The material must have good

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wetting properties with surface tension. The penetrant must be suitable for capillary action. If a developer is used, the penetrant material must be able to be absorbed by the developer in a uniform manner.

Specific requirements

Control of contaminants

The certification of contaminant content for all liquid penetrant materials used on nickel-base alloys, austenitic stainless steels, and titanium shall be obtained and reviewed. These certifications shall include the penetrant manufacturers' batch numbers and the test results obtained in accordance with (a) and (b) in the following section.

These records shall be maintained for review as required.

(a) When examining nickel-base alloys, all materials shall be analyzed individually for sulfur content as follows.

- **(1)** An individual sample of the penetrant materials, with exception of cleaners, shall be prepared for analysis by heating 50 g of the material in a 150-mm nominal-diameter glass Petri dish at a temperature of 194–212°F (90–100°C) for 60 min. This method must be done in a properly ventilated laboratory room to dissipate the emitted vapor generated by the process.

  The residue is evaluated and analyzed to meet the following limits to be acceptable.
  - The residue should be ≤ 0.0025 g for the material to be is acceptable.
  - The sulfur content should be $\leq 1\%$ of the residue by weight.
- **(2)** The cleaner and remover material is similarly tested. A sample of the material is prepared for analysis by heating 100 g of the material in a 150-mm nominal-diameter glass Petri dish at a temperature of 194–212°F (90–100°C) for 60 min.

  The residue is evaluated and analyzed to meet the following limits.
  - The residue should be ≤ 0.005 g for the material to be acceptable.
  - The sulfur content should be $\leq 1\%$ of the residue by weight.

(b) For examining austenitic stainless steel or titanium, the importance of contaminates like chlorine and fluorine assumes importance. The following tests are carried out to determine these contaminants.

- **(1)** The penetrant materials sample is prepared for analysis. A sample of 50 g in a 150-mm diameter glass Petri dish is heated at a temperature of 194–212°F (90–100°C) for 60 min.

  If the residue is ≤ 0.0025 g, the penetrant is acceptable.

  ASME SE 165 gives alternative test methods for testing chlorine and fluorine where the combined residue shall be less than 1% by weight.
- **(2)** Similarly, the 100 g sample of cleaner material in a 150-mm glass Petri dish is tested at a temperature of 194–212°F (90–100°C) for 60 min.

  The acceptable amount of residue is ≤ 0.005 g.

  ASME SE 165 gives another alternative technique of ion chromatography for PT cleaner/remover material for chloride and fluoride.

Surface preparation

The surface preparation is very important for obtaining satisfactory results of PT.

(a) For parts to be tested in as-welded, as-rolled, as-cast, or as-forged condition, the surface is prepared by grinding, machining, or other methods that are not capable of blocking the surface opening of the possible discontinuities.
(b) Prior to the liquid penetrant examination, the target area and about 25 mm adjacent areas on the surface is visually examined to ensure that the material is dry and free of all dirt, grease, lint, scale, welding flux, weld spatter, paint, oil, and other extraneous matter that could obscure surface openings or otherwise interfere with the examination.
(c) The cleaning agents used to remove contaminants from the surface are detergents, organic solvents, descaling solutions, paint removers, etc. as the requirement of the specific part to be examined; more than one agent may be used in some cases. Degreasing and ultrasonic cleaning methods are also used.

Drying after preparation

Surfaces to be examined are dried after cleaning. Drying is done by normal evaporation or with forced hot or cold air. It must be ensured that the cleaning solution has evaporated prior to application of the penetrant.

Techniques

Fluorescent penetrant or visible penetrant with color contrast are used with one of the following three penetrant processes:

(a) Water-washable
(b) Postemulsifying
(c) Solvent-removable

The combination of the fluorescent or visible penetrates with these three processes results in six liquid penetrant techniques.

Techniques for standard temperatures

The general application of the techniques is for material surface being above 10°C (50°F) but below 50°C (125°F). This temperature range is maintained throughout the testing period.

Penetrant application

The penetrant is applied by a suitable means, such as:

(a) Dipping the component in the penetrant
(b) Brushing the penetrant on the surface to be examined
(c) Spraying the penetrant on the surface to be examined

If the spraying method is used for application of the penetrant, proper filters must be used to control contaminants like oil, water, dirt, or sediment that may have collected in the compressed air lines.

Table 3-5-1 Minimum dwell time.

Material	Form of material	Type of targeted discontinuity	Dwell time (in min) (at 10–50°C)	
			Penetrant	**Developer**
Aluminum, magnesium steel brass bronze, titanium, high-temperature alloys	Casting and welds	Cold shuts, porosities, lack of fusion, all types of cracks	5	7
	Wrought material-plates, forgings, extrusions	Laps, all forms of cracks	10	7
Carbide-tipped tools		Lack of fusion, porosities, cracks	5	7
Plastics	All forms	Cracks	5	7
Glass	All forms	Cracks	5	7
Ceramics	All forms	Cracks, porosity	5	7

Penetration time (dwell time)

Penetration time is critical. The minimum penetration time is often established, and it is generally regulated by the testing code general guideline on dwell time given in Table 3-5-1.

Excess penetrant removal

After the specified penetration time has elapsed, any remaining penetrant on the material surface is removed. Care is taken to ensure that only surface excess is removed, and no attempt is made to remove penetrant from discontinuities. Different penetrants require specific care for removal.

Removing excess water-washable penetrant

As the name implies, the excess water-washable penetrant is removed by spraying water. The water pressure is kept below 50 psi (345 kPa), and the temperature of water is maintained below 110°F (43°C). Care must be taken to remove only the excess penetrant on the surface and not from the crevices and cracks that need to be evaluated.

Removing excess postemulsifying penetrant

The postemulsifying penetrant is applied by spraying or dipping. The emulsification time is critical. The dwell time is governed by surface roughness and type of applied emulsifier. The dwell time is qualified by actual tests. After emulsification, the mixture is removed by water spray similar to the procedure used for water-washable penetrant.

Removing excess solvent-removable penetrant

Excess solvent-removable penetrant is removed by wiping with a lint-free cloth or absorbent paper, repeating the operation until most traces of the penetrant is removed from the surface. The remaining traces are removed by lightly wiping the surface with a lint-free cloth or absorbent paper moistened with solvent. Excess solvent must be avoided to minimize removal of penetrant from discontinuities.

Drying process after excess penetrant removal

The surface for water-washable and postemulsifying penetrant process can be dried by blotting with clean materials or by using circulating air, keeping the temperature of the surface below 125°F (50°C).

The drying in the solvent-removable process is by forced air or normal evaporation, blotting, or by wiping the surface with a lint-free cloth or paper.

Developing

The developer is applied immediately following the removal of the excess penetrant from the surface. A uniform and reasonable layer of the developer is applied. Insufficient coating thickness may not draw the penetrant out of discontinuities; conversely, excessive coating thickness may mask indications.

When using color contrast penetrant, only a wet developer is used. If, however, a fluorescent penetrant is selected, then either wet or dry developer is used.

- **Dry Developer Application**

  Dry developer is applied on a dry surface by a soft brush, hand powder bulb, powder gun, or other means. The object is to dust the powder evenly over the entire surface to be examined.
- **Wet Developer Application**

  The suspension-type wet developer must be properly shaken prior to the application. This ensures adequate dispersion of suspended particles.

  Application of Aqueous Developer:

  Aqueous developer is applied to either a wet or dry surface. The developer is applied by either by dipping, brushing, spraying, or other means, provided that a thin layer of coating is obtained over the entire surface to be examined.

Application of nonaqueous developer

Nonaqueous developer is applied only to a dry surface. Mostly, it is applied by spraying. Sometimes, due to safety reasons, spraying is not possible, then the developer is applied by brushing. Normal evaporation process is used to dry the developer.

Developing time for final interpretation starts immediately after the application of a dry developer or as soon as a wet developer coating is dry. The minimum developing time is given in Table 3-5-1.

Interpretation

Final interpretation

Final interpretation shall be made within 7–60 min. After the dwell time of the developer. If bleed-out does not alter the examination results, longer periods are permitted. If the surface to be examined is large enough to preclude complete examination within the prescribed or established time, the examination is performed in increments.

Characterizing indication(s)

Some types of discontinuities are difficult to evaluate, especially if the penetrant diffuses excessively into the developer. In such conditions, the application and interpretation must be carried out simultaneously to observe the formation of indication(s). This is helpful in characterizing the nature of the indication, and it helps to determine the extent of the indication(s).

Color contrast penetrant

In the color contrast penetrant process, the developer forms a reasonably uniform white coating. Surface discontinuities are indicated by bleed-out of the penetrant, which is normally a deep red color that stains the developer. Indications with a light pink color may indicate excessive cleaning. Inadequate cleaning may leave an excessive background making interpretation difficult. A minimum light intensity of 50 fc (500 Lux) is required to ensure adequate sensitivity during the examination and evaluation of indications.

Fluorescent penetrant

The fluorescent penetrant process is similar to the color contrast process except that the examination is performed using an ultraviolet light, which is also called black light.

The examination process is sequenced below.

(a) The test is performed in a dark room or dark enclosure.
(b) The examiner is in the dark area for at least 1 min prior to performing the examination to enable his eyes to adapt to dark viewing. If the examiner wears glasses or lenses, they shall not be photosensitive.
(c) The black light is allowed to warm up for a minimum of 5 min prior to use or measurement of the intensity of the ultraviolet light emitted.
(d) The black light intensity is measured with a black light meter. A minimum light intensity of 1000 mW/cm^2 on the surface of the part being examined is required. The black light intensity is measured at least once every 8 h and whenever the workstation is changed.

Evaluation

All indications are evaluated in terms of the acceptance standards of the applicable inspection code.

The interpreter shall be able to distinguish the discontinuities at the surface indicated by bleed-out of penetrant and false indications caused by the localized surface irregularities due to machining marks or other surface conditions.

Broad areas of fluorescence or pigmentation should be avoided as they tend to mask indications of discontinuities; if such conditions exist, the affected area should be cleaned out and reexamined.

Fluorescent penetrant examination shall not follow a color contrast penetrant examination. Intermixing of penetrant materials from different families or different manufacturers should not be done.

Liquid penetrant comparator

Testing beyond 10–52°C temperature range

The liquid penetrant comparator blocks are used when the test is required to be conducted outside the 50–125°F (10–52°C) temperature range.

The process involves comparator blocks made of 3/8-inch-thick rectangular aluminum plates of a specific grade.

The procedure

On the given test block, an area is marked at the center of both faces; the marked area is approximately 1 in. (25 mm) in diameter. The mark is made with a 950°F (510°C) temperature-indicating crayon. The marked area is then heated with a torch or burner to a temperature between 950°F (510°C) and 975°F (524°C). The specimen is then immediately quenched in cold water, and this produces a network of fine cracks on each face. After cooling, the block is cut in half. One-half of the specimen is marked as block "A," and the other block is marked "B" for identification.

Comparator application

If it is desired to qualify a liquid penetrant examination procedure at a temperature of less than 50°F (10°C), the proposed procedure shall be applied to block "B" after the block and all materials have been cooled and held at the proposed examination temperature until the comparison is completed.

The standard procedure that is previously used to demonstrate at block "A" in the 50–125°F (10–52°C) temperature range is used on block "B" for the lower temperature.

The indications of cracks shall be compared between blocks "A" and "B." If the indications obtained under the proposed conditions on block "B" are essentially the same as obtained on block "A" during examination at 50–125°F (10–52°C), the proposed procedure shall be considered qualified for use.

Ultrasonic testing

6

An introduction to the world of sound

Physicists and acoustic engineers tend to discuss sound pressure levels in terms of frequencies, partly because this is how our ears interpret sound. What we experience as "higher pitched" or "lower pitched" sounds are pressure vibrations having a higher or lower number of cycles per second. In a common technique of acoustic measurement, acoustic signals are sampled in time, and then presented in more meaningful forms such as octave bands or time frequency plots. Both these popular methods are used to analyze sound and better understand the acoustic phenomenon.

The fundamental principles being same, there are more advanced developments in the field and basic principles are dissected and utilized to address more specific needs of the ever-growing industry. Some of these specialized "subsections" or new developments in ultrasonic testing are listed here. In this chapter, some of these will be addressed, but for further detail, the readers are directed to the specialized industry expert companies as some of these are very proprietary techniques.

- UT—Shear-Wave Ultrasonic Testing
- AUT—Automated Ultrasonic Testing
- PAUT—Phased-Array Ultrasonic Testing
- TOFD—Time of Flight Diffraction Ultrasonic Testing
- GWUT—Guided-Wave Ultrasonic Testing
- LGWUT—Long-Range Guided-Wave Testing
- SWUT—Surface-Wave Ultrasonic Testing

Theory of sound wave and propagation

In fluids such as air and water, sound waves propagate as disturbances in the ambient pressure level. Although this disturbance is usually small, it is still audible to the human ear. The smallest sound that a person can hear, known as the threshold of hearing, is nine orders of magnitude smaller than the ambient pressure. The loudness of these disturbances is called the sound pressure level and is measured on a logarithmic scale in decibels. Mathematically, sound pressure level is defined as:

$$\mathrm{SPL} = 20 \times \log_{10}\left(P/P_{ref}\right)$$

where:

P_{ref} is the threshold of hearing
P is the change in pressure from the ambient pressure

Table 3-6-1 gives a few examples of sounds and their strengths in decibels and Pascals.

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Table 3-6-1 Pressure amplitude and decibel level.

Example of common sound	Pressure amplitude (Pa)	Decibel level (dB)
Threshold of hearing	$20*10^{-6}$	0
Normal talking at 1 m	0.002–0.02	40–60
Power lawnmower at 1 m	2	100
Threshold of pain	200	134

The entire sound spectrum can be divided into three sections: audio, ultrasonic, and infrasonic. The audio range falls between 20 and 20,000 Hz. This range is important because its frequencies can be detected by the human ear. This range has a number of applications, including speech communication and music.

The ultrasonic range refers to the very high frequencies: 20,000 Hz and higher. This range has shorter wavelengths, which allow better resolution in imaging technologies. Industrial and medical applications such as ultrasonography and elastography rely on the ultrasonic frequency range.

On the other end of the spectrum, the lowest frequencies are known as the infrasonic range. These frequencies can be used to study geological phenomenon such as earthquakes, etc.

As stated earlier in the introduction, the term *ultrasonic* is the name given to the study and application of sound waves having frequencies higher than those that can be heard by human ears.

Ultrasonic nondestructive testing is the use of the ultrasonic sound spectrum to examine or test materials or measure thickness without destroying the material. The testing frequencies range from 100,000 cycles per second (100 kHz) to 25,000,000 cycles per second (25 MHz).

Ultrasonic testing does not give direct information about the exact nature of the discontinuity. This is deduced from a variety of information, such as the material's property and its construction.

Theory of sound

Sound is mechanical vibrations of particles in a medium. When a sound wave is introduced in a material, the particles in the material vibrate about a fixed point at the same frequency as the sound wave. The particles do not travel with the wave but react to the energy of the wave. It is the energy of the wave that moves through the material.

The length of a particular sound wave is measured from trough to trough, or from crest to crest. The distance is always the same. This distance is known as the wavelength (λ). The time taken for the wave to travel a distance of one complete wavelength (λ) is the same amount of time it takes for the source to execute one complete vibration. The velocity of sound (V) is given by the following equation.

$$V = \lambda * F$$

Where:

λ = the wavelength of the wave
F = the frequency of the wave

A number of sound waves can travel through solid matter, and some of them are listed here.

The **longitudinal wave** is also called a compression wave. The particles vibrate back and forth in same direction as the motion of the sound. The ultrasonic vibrations in liquids and gases propagate in longitudinal waves only. This is because liquids and gases have no shear rigidity.

A **shear wave** is also called a transverse wave. The particles in this type of wave vibrate back and forth in a direction that is at a right angle to the motion of sound.

It is also possible, in some specific limits, to produce shear waves that travel along the free boundary or surface of a solid. These **surface or Rayleigh waves** penetrate the material to a depth of only a few particles.

In solids, all the three modes of sound waves can propagate.

The shortest ultrasonic wavelengths are of the order of the magnitude of the wavelength of visible light. Because of this, ultrasonic wave vibrations possess properties very similar to light waves in that they can be reflected, focused, and refracted.

High-frequency particle vibrations of sound waves are propagated in homogeneous solids in the same manner as directed light beams. Sound beams are reflected either partially or totally at any surface acting as a boundary between the object and the gas, liquid, or other type of solid. The ultrasonic pulses reflect from discontinuities, thereby enabling detection of their presence and location. Some of the terminology specially associated with ultrasonic testing methods is described in the following.

Piezoelectricity

Piezoelectricity refers to the electricity produced by a vibrating crystal and its phenomenon to reverse back to vibrating of the crystal.

When electric current is applied into the crystal, the crystal transforms the electrical energy to mechanical vibrations and transmits the vibrations through a coupling medium into the test material. These pulsed vibrations propagate through the object with a velocity that depends on the density and elasticity of material.

Sound beam reflection

High-frequency sound waves act in a similar way as light waves. If the wave is interrupted by an object, most of the sound beam is reflected. Crystals or transducers then pick up these sound beams and present them as vertical deflections of a horizontal trace or a line base on a cathode ray tube (CRT) or an oscilloscope. This type of presentation is called an A-scan; other presentations include B-scan, which presents a cross-sectional image of the discontinuity and the material being inspected, and C-scan, which displays the discontinuity in plain view.

Sound beam frequencies

Most ultrasonic testing is available within 400 kHz to 25 MHz. These vibrations are beyond the audible range and propagate in the test material as waves of particle vibrations. Sound beams of all frequencies can penetrate fine-grained material without difficulty. When using high frequencies in coarse-grained material, interpretation becomes difficult as interference in the form of scattering is noted. Depth of penetration is better achieved by lower frequencies.

The selection of a specific frequency for testing is mainly dependent on the material's property and goal of the testing.

Frequencies up to 1 MHz are generally a good choice, and they have better penetration, less attenuation, and scatter less by coarse grains and rough surfaces. The disadvantage of low frequencies is that they have a large angle of divergence and, as such, they can't resolve small flaws.

On the other side, the high-frequency transducers emit more concentrated beams with better resolving power, but they are more scattered by coarse grains and rough surfaces.

Frequencies above 10 MHz are normally not used in contact testing, because the higher-frequency transducers are thinner and fragile. As the frequency of sound vibrations increase, the wavelength correspondingly decreases and approaches the dimension of the molecular or atomic structure. In an immersion testing, however, all frequencies can be used because there is no physical contact between the transducer and the material being tested.

Sound beam velocities

Ultrasonic waves travel through solids and liquids at relatively high speed, but they are relatively rapidly attenuated or die down. The velocity of a specific mode of sound is a constant through a given homogeneous material. The ultrasonic wave velocities through the various materials are given in Table 3-6-2. The difference in sound velocity is due to the difference in density and elasticity of each material. Yet, it may be noted that density alone is not able to account for the variations; it may be noted that beryllium has high sound velocity, although it is less dense than aluminum, and the acoustic velocity of water and mercury is nearly the same, although the density of mercury is 13 times greater than water.

While discussing properties of sound, we introduced that the sound beams are refracted and subjected to mode conversion, resulting in a combination of shear and longitudinal waves. What are the principles governing the mode of transformation?

Table 3-6-2 Sound velocities in various mediums.

		Longitudinal velocity	
Material	**Density (g/cm^3)**	**cm/µs**	
Air	0.001	0.033	738
Water	1.00	0.149	3333
Plastic (Acrylic)	1.18	0.267	5972
Aluminum	2.8	0.625	13,981
Steel		0.56	
Cast Iron		0.35–0.56	
Mercury	13.00	0.142	3176
Beryllium	1.82	1.28	28,633

When a longitudinal ultrasonic wave is directed from one medium into another of different acoustic properties at an angle other than normal to the interface between the two media, a wave mode transformation occurs. The resultant transformation is dependent upon the incident angle in the first medium and on the velocity of sound in the first and second media. In each transformation, there is an equal angle of reflection back into the first medium. Snell's law is used to calculate angle transformations based on the sound path angles and the sound velocities of the two media (Figure 3-6-1).

Snell's law of reflection and refraction

Observing the sketch describing Snell's law of reflection and refraction, we note that the sine of the incident angle a is to the sine of d (longitudinal) or e (shear) refracted angle as sound velocity of the incident medium 1 is to the sound velocity of the refracted medium 2. The same relation exists when mode conversion occurs within the same medium, using the sound velocities of different waves in the equation. This can be used to calculate refracted and reflected angles. For part A of the sketch, these equations can be written as:

$$\sin a/\sin d = \text{Longitudinal velocity in medium-1}/\text{Longitudinal velocity in medium-2.}$$

$$\sin a/\sin e = \text{Longitudinal velocity in medium-1}/\text{Shear velocity in medium-2.}$$

or

$$\sin a\,(\text{long})/\sin c\,(\text{shear}) = \text{Longitudinal velocity in medium-1}/\text{Shear velocity in medium-1.}$$

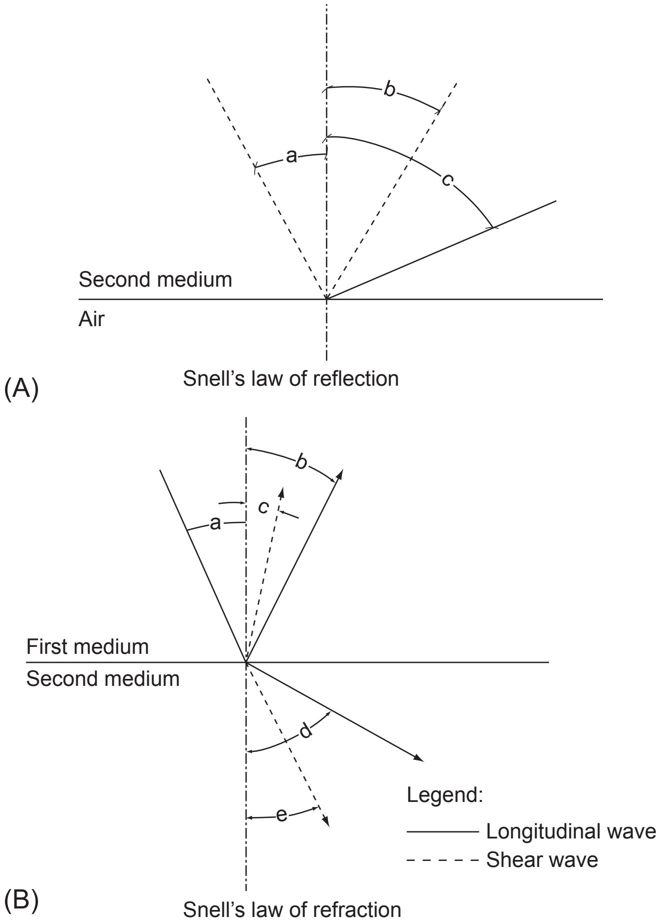


Figure 3-6-1 (a) and (b) Snell's law of reflection and refraction.

In the B part of the sketch, the equation will be:

$$\sin a\,(\text{shear})/\sin c\,(\text{long}) = \text{Shear velocity in medium-2}/\text{Longitudinal velocity in medium-2.}$$

We note that, as the incident angle is increased from normal, this results in only the longitudinal wave. This longitudinal angle d also increases until it reaches 90 degrees, and at that point, no more longitudinal waves enter the second medium. This angle of the medium is called **First Critical Angle**.

As the incident angle is further increased, the shear angle e also increases until it becomes 90 degrees, and at this point the entire shear wave in the second medium is transformed into the surface wave. This is called **Second Critical Angle**.

These calculations use simple centerline of the beam as input; the actual application, however, is more complex as the sound beam has width and divergence. The amplitude of the sound is also higher at its centerline, and it gradually dies down on the outer edges.

Understanding the variables associated with ultrasonic testing

The sound velocity through a given material is the distance that sound energy will propagate in that material in a given time and is a function of material density, material's acoustic impedance, and its temperature.

Because sound velocities are relatively high, most expressions are in meters or feet per second. The sound velocity of a shear wave in a given material is usually one-half of a longitudinal wave and about 1.1 times that of a surface wave. Specific velocities are tabulated in handbooks and are used for calculations to determine the angle transformations.

The effect of temperature on sound velocity is normally not very significant in most metals but must be considered when calculating angles in plastics if they are used as a wedge for shear wave search units.

The frequency of ultrasound used for testing is usually between 1 and 6 MHz. Most common frequency for weld inspection is 2.25 MHz. The transducer element when exiting resonates at its natural frequency. The resulting frequency is not a single frequency but a relatively narrow band of frequencies. Of these, one or more will be respond with the highest amplitude. The frequency is related to the thickness of the transducer element. Frequency is decreased as the thickness of the element is increased.

The piezoelectric property of the transducer is affected by the natural frequency of the element and must be considered to obtain maximum sound amplitude. It may be noted that broadband pulse generation is usually effective and used with portable equipment.

As explained earlier in the theory of sound, the wavelength (λ) is the function of velocity (V) and frequency (F).

$$V = \lambda * F$$

The expected minimum size of reflector (flaw) detectable with ultrasonic sound is about one-half wavelength (λ/2) as measured in a direction perpendicular to the direction of sound propagation.

Selection of test equipment

A variety of ultrasonic test applications have prompted the industry to develop specialized test equipment. The enormous development of electronics has allowed manufacturers to add more sophisticated functional features to their equipment, increasing portability, better results, and taking away several calculations from the hands of the operators and adding them to the machine as features. Equipment that is smaller in size and higher in speed are very common features of this new equipment. Other developments include:

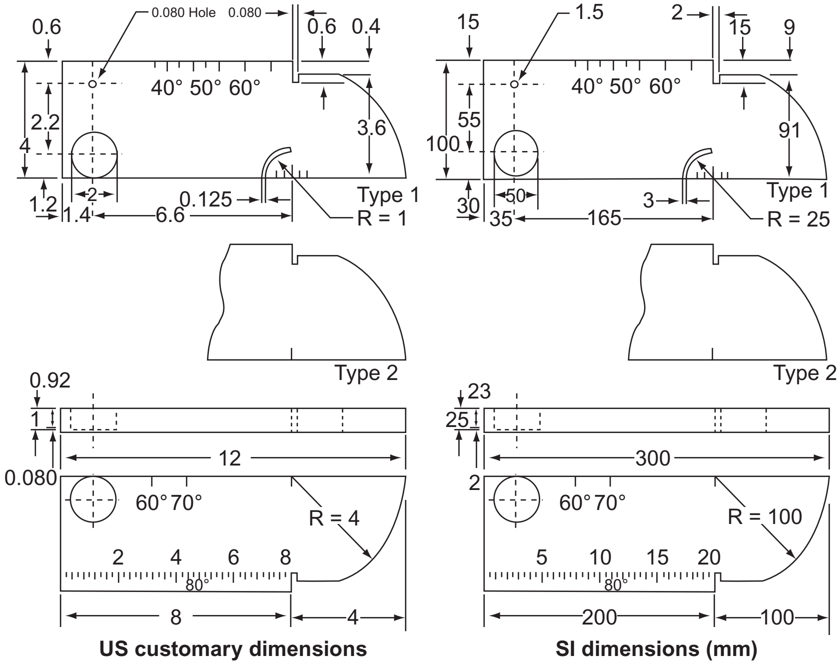
- Real-time 320 × 240 pixel (QVGA)
- A-Trace (40 Hz update) display
- Distance Amplitude Flaw Gating (DAG)
- Weld Trig
- Freeze and Insta-Freeze for Spot Weld Applications
- Precision Thickness Measurement capability
- Combined Flaw and Thickness Mode
- 2 Megabyte of memory for substantial storage capability
- USB connectivity
- High Speed Scrolling and Encoded B-Scan
- IP and IF Gating
- Adjustable Damping
- Multicolor LCD screens
- Other features such as SplitView, SplitScan, and AutoTrack, and Quarter VGA resolution etc. are offered by manufacturers.

But in its very basic form, the ultrasonic principles are the same, and available equipment is based on those principles. Longitudinal wave ultrasound is generally limited in use to detecting inclusions and lamellar-type of discontinuities in the base material. Shear waves are most valuable in detection of weld discontinuities because of their ability to furnish three-dimensional coordinates for discontinuities. As stated earlier in this section, the sensitivity of a shear wave is about twice that of a longitudinal wave, the frequency and search unit size being constant.

Shear wave angle is measured in the test material from a line perpendicular to the test surface. The search unit's angle selection is based on the expected flaw orientation. Usually, it is a good practice to use more than one search angle to ensure proper detection of flaws. Three most common angles used for shear wave testing are 70-, 60-, and 45-degree probes (Figure 3-6-2).

A-scan equipment

In the A-scan system, the data is presented as a returned signal from the material under test. The data is presented on an oscilloscope. The horizontal base line on the oscilloscope screen indicates from left to right the elapsed time, and the vertical deflection shows signal amplitude. For a given velocity in the specimen, sweep can be calibrated directly across the screen, in terms of distance or depth of penetration into the sample. Conversely, when the dimension (thickness) of the specimen is known, the sweep time may be used to determine ultrasonic velocities. The height of the indications, or "pips," represents the intensities of the reflected sound beams. These are used to determine the size of the discontinuity, depth, or distance to discontinuity from any given surface the sound beam is either entering or reflecting back. The main advantage of this type of presentation is that it gives the amplitude that can be used to determine the size and position of the discontinuity.



Notes:

1. The dimensional tolerance between all surfaces involved in retaining or calibrating shall be within +0.005 in. (0.13 mm) of detailed dimension.
2. The surface finish of all surfaces to which sound is applied or reflected from shall have a maximum of 125 µin. r.m.s.
3. All materials shall be ASTM A36 or acoustically equivalent.
4. All holes shall have a smooth internal finish and shall be drilled 90 degrees to the material surface.
5. Degree lines and identification marking shall be indented into the material surface so that permanent orientation can be maintained.
6. Other approved reference blocks with slightly different dimensions or distance calibration slots are permissable.

Figure 3-6-2 Typical calibration blocks for UT testing.

B-scan equipment

The B-scan is especially useful when distribution and shape of large discontinuities within a sample cross-section is of interest. In addition to the basic components of the A-scan equipment, the B-scan provides the following functions.

1. Retains the image on the oscilloscope screen by use of a long persistence phosphor coating.
2. Deflection of the image-tracing spot on the oscilloscope screen is synchronized with motion of the transducer along the sample.
3. Image-tracing spot-intensity modulation or brightness is in proportion to the amplitude of the signals received.

C-scan equipment

C-scan equipment are intended to provide a permanent record of the test when high speed automatic scanning is used in ultrasonic testing. C-scan equipment displays the discontinuities in a plan view. It does not give the depth or orientation of the discontinuity.

Testing procedure

Most of the testing is carried out as per the written procedures for a specific work. These are based on the applicable code of construction. Hence the discussion here is of general application, and specifics must be developed meeting the work requirements.

Prior to the testing with shear wave angle units, it is good practice and some codes mandate that the material is scanned with a longitudinal unit to ensure that the base material is free from such discontinuities that would interfere with shear wave evaluation of flaws.

Some of the basic rules of testing are listed here.

1. The sound path distance is basically limited to a specified limit, generally up to 10 in.
2. Three basic search unit angles are used 70, 60, and 45 degrees, as measured from a line normal to the test surface of the material.
3. It is assumed that any flaw will be normal to the test material surface and parallel to the weld axis. The flaw orientation would be the most serious direction for flaws in most welds.
4. The 70-degree search unit would provide the highest amplitude response from the type of flaw described before, followed by 60- and 45-degree search units. Hence the order of preference in use shall be the same.
5. The relative amplitude response from the flaw is in direct proportion to its effect on the integrity of the material and weld. The generally accepted diminishing order of flaw severity in welds and material is given as:
    - **a.** Cracks
    - **b.** Incomplete fusion
    - **c.** Incomplete penetration
    - **d.** Inclusions (slag, etc.)
    - **e.** Porosity
6. Ultrasonic indications are evaluated on decibel amplitude basis. Each indication to be evaluated is adjusted with the calibrated dB gain or attenuation control to produce a reference level height on the CRT, and the decibel setting number is recorded as indication level a.
7. The reference level b is attained from a reflector in an approved calibration block. The reflector indication is maximized with search unit movement and then adjusted with the gain or attenuation control to produce a reference level indication. This decibel reading is reference level b.
8. The decibel attenuation factor c is used for weldment testing at the rate of 2 dB per in. of sound path after the first inch. For example, a 6-in. sound path would produce an attenuation factor of $(6-1)\times 2=10$.
9. Decibel rating d, for flaw evaluation, is in accordance with the construction code requirement; with gain control, this is attained by applying equation $a-b-c=d$. However, for equipment with attenuation control, $b-a-c=d$.

Case studies associated with actual calibration testing of welds are included.

Role of coupling in testing

The couplant material is used to maintain full contact of the transducer with the material surface. This allows the transfer of the sound wave. It also helps full coverage of the test surface during testing.

Coupling material should be hydraulic in nature and have good wetting property to cover the material surface. The couplant materials used include water, oil, grease, glycerin, and cellulose gum powder mixed with water.

The cellulose gum powder is most common material used for testing. It has significant advantages over the others as it is low cost, its viscosity can be changed with addition of more water, it is not a slipping hazard, it does not form a contaminant film on the material surface, and its residue is easily removable, hence it is not an obstacle for any further work like repair involving welding, etc.

Prior to testing, the equipment is checked for linearity and calibrated to cover the scope of work. The calibration blocks used for calibrating UT equipment before testing can be standard or very specific to the task at hand. A typical IIW block is shown in the following sketch. Both US Customary unit and Metric unit calibration blocks are shown. Note that the block has a beam exit angle for correcting the correct angle of the sound beam exit from the transducer. This is an important step in accuracy of testing. Most standards and codes mandate that, prior to start of calibration and testing, the beam exit angle is reestablished, and all future calculations are based on the correct angle of the beam path.

This is one of the basic calibration steps; further detailed calibration steps are involved for testing.

Automization of ultrasonic testing systems

At the start of this section of ultrasonic testing, we introduced some terms like AUT, TOFD, Pulse-echo, etc. We will discuss a few of these as introductory terms, as more and more UT inspections are now being done by automated systems and introduction to this is necessary. Most of the automated UT (AUT) systems are applied to and associated with girth welds, but that is not to assume that the technique is not used for longitudinal butt weds.

Techniques used are to be based on zonal discrimination of weld cross-sections, whereby the weld is divided into approximately equal vertical inspection sections (zones), each being assessed by a pair of ultrasonic transducers. These inspection zones are typically of 2–3 mm (0.08–0.12 in.) in height. For most applications, this requires the use of contact-focused transducers. This is essential to avoid excessive overlap with adjacent signals and interference with signals originating from off-axis geometric reflectors. The system is able to provide an adequate number of inspection channels to ensure the complete volumetric examination of the weld through thickness in one circumferential scan. The instrument is capable of providing a linear A-scan presentation for each selected channel. The AUT inspection channels allow the volume of the weld scanned to be assessed in accordance with the inspection zones.

It is important to have calibrated instrument linearity within 5% of the ideal acceptable linearity for both linear and logarithmic amplifiers. Each inspection channel is suitable for selecting pulse-echo or through-transmission mode, gate position and length for a minimum of two gates, and gain.

Recording thresholds are set so that the system can select display signals between 0% and 100% of full-screen height for simple amplitude and transit time recording, and from 0% to 100% for B-scan or “mapping”-type recording of data. The B-scan mapping is described later. Two recordable signal outputs per gate are available, in either analog or digital form, and they are representative of signal height and time of flight. These systems are made suitable for recording on a multichannel recorder or computer data acquisition software display.

The recording system

A marker circuit suitable for connection to the recorder or acquisition system is used, and its accuracy is very important for full and proper coverage of the weld, especially the circumferential welds. This acquisition is important too as means of electronically determining circumferential weld distance to an accuracy of at least ±10 mm (0.4 in.). Often an optical encoder is used as a distance marker. Programmed scan lengths are to ensure that all probes cover the maximum circumferential distance required for a given circumference of the weld. A suitable correction factor is used for equipment that have the encoders traveling on a track or welding guide-band to ensure the circumferential distance recorded on the chart corresponds to the transducer position on the circumferential weld outer surface. Each transducer for weld discontinuities records for confirmation of the acoustic coupling arranged on the chart or display.

Mapping (TOFD)

B-scan or “mapping” displays are used for volumetric flaw detection and characterizations, and time of flight diffraction (TOFD) techniques are often added to improve characterization and sizing. TOFD techniques are often used to augment pulse-echo techniques; however, a TOFD technique is not intended to replace pulse-echo techniques.

Where TOFD technique is used for mapping, the recording system should be capable of a 256-level gray-scale display and be capable of recording full R-F waveforms for the TOFD transducer pairs.

This is only a brief atypical AUT system. The details of AUT inspection of welds should be assessed; often, an engineering-critical assessment is carried out to assess the level of critical flaws that should be evaluated and accepted or rejected. The selection of specific equipment and its limits and advantages should be evaluated in terms of a specific quality level required for a specific weld.

Eddy current testing

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The eddy current testing process is also called electromagnetic testing. The method is based on the general principle that an electric current will flow in any conductor subjected to a changing magnetic field.

Depending on the type and thickness of material being tested, the testing frequencies vary from 50 Hz to 1 MHz. The method is used to check welds in magnetic and nonmagnetic material and is particularly useful in testing bars, billets, welded pipes, and tubes.

Method

In the eddy current testing method, electric current—either eddy or Foucault current—is induced in the test piece, and the changes in those current are measured. The changes occur because of the presence of discontinuities. The test measures the resistivity caused by changes in chemical composition, crystal orientations, heat treatment hardness, or discontinuities.

Commercial test methods have developed systems that use excitation coils and large magneto-resistance sensors, also called GMR, with adequate system controls in place. The magnetic induction fields are introduced in the material or weld to be tested through eddy current probes (ECP). The control systems often use sinusoidal signal generators as part of the comprehensive system.

The process starts with the production of an excitation current by a transadmittance amplifier, which is driven by a generator. The voltage signal obtained from the eddy probe through the GMR are amplified on the low noise set on some acceptable gain value. The detected signal is applied to an analog input processor at about 1.2 MHz. The signals are processed to produce eddy current image of the flaw, with x and y coordinates for analysis.

Other image-improving and processing systems are added to improve the readability of flaws.

Advantages and disadvantages of eddy current inspection system

The eddy current inspection process has some very significant advantages and corresponding limitations as listed here.

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Advantages

1. The sensitivity to surface defects is excellent, and the system can detect defects of 0.5 mm in length.
2. The system can penetrate through several layers of planar interface to detect defects.
3. Coating up to about 5 mm thick need not be removed for the application of the eddy current inspection process.
4. The system has the ability to measure accurate conductivity through the use of dedicated conductivity measurement instruments.
5. Preinspection cleaning is not a major concern if major soils and loose or uneven surface coatings are removed prior to inspection.
6. The system is often automated, and this allows for quick turnaround on mass inspection of products.
7. The system is portable allowing it to be used in hard-to-reach spots.

Limitations

1. The system is very susceptible to magnetic permeability changes. Small changes in material permeability can have a pronounced effect on the eddy currents, especially in ferromagnetic materials. This makes testing of welds and other ferromagnetic materials difficult but, with modern digital flaw detectors and probe design, not impossible.
2. The eddy current inspection system is effective only on conductive materials. The system works only on conductive materials able to support a flow of electrical current.
3. The eddy currents always flow parallel to the surface. If a planar defect does not cross or interfere with the current, then the defect will not be detected.
4. The flow of eddy current cannot resolve complex geometries of the work to be inspected. The system also has a limitation on large areas to be inspected. Large-area scanning can be accomplished with the help of additional aid of special scanning device, supported by a computer, both of which are not inexpensive.
5. Due to the many factors that affect eddy currents, good training and expertise are required to interpret eddy current signals. Care is required to distinguish between relevant and nonrelevant indications.
6. Unless an automated system is used, the inspection data record is not permanent. Normally, the only permanent record will be a paper printout or computer file when using automated systems.

Acoustic emission testing (AET)

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The application of acoustic emission testing (AET) includes detection of possible cracks in a vessel or structure. This is done on the principles that a sound structure would stop emitting signals once the load is reduced, and does not emit any further bursts until a pervious load is exceeded. A growing crack would emit an increasing signal as it is loaded, thus making it easier to locate the crack.

AET has been successfully applied to welded pressure vessels and other welded structures during proof testing to determine the growth of cracks during pressurization. AET is often used as a surveillance method to monitor potential failures in the in-service vessels and structures. As the vessel or structure is loaded and cracks grow, it emits an increasing decibel distinct from the rest of the acoustic signals. These signals are presented in a wide frequency spectrum along with ambient noise from many other sources. The transducers are strategically located on a structure and activated by arriving signals. By use of proper filtering, the ambient noise in the composite signal is significantly reduced, and a source of significant signals is plotted by triangulation based on the arrival time of these signals at different transducers.

Ongoing developments in AET field

American Society of Mechanical Engineers (ASME) has developed a "Standard for AE Examination During Application of Pressure"; similarly, American Society for Testing Materials (ASTM) Committee E-7 that looks after nondestructive testing is engaged in developing standard terminology for acoustic emission (AE), transducers, method of applications, acoustic waveguides, etc. This committee is also engaged in developing recommended practices for calibration of frequency response. The ASTM committee also deals with AE instrumentations such as recommended practice for performance of event counting and locating systems, and applications of AET.

The application of AET in weld-testing is also useful, especially where delayed cracking is possible in the material.

Future of AET

AET equipment has evolved to a very refined state over a long development period. The evaluation of AET source and signals need further development and standardization. Use of AET during proof-testing is of value to fabricators and users, and it offers promise of wider application. AET monitoring can improve production control of welding during fabrication.

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Selection of NDE methods. Application and limitations for specific cases: Case study 3

We have noted in the text of this book that, in selecting the nondestructive evaluation (NDE) method for the evaluation of a specific discontinuity, the methods can work as complimentary to each other. Several NDE methods may be able to perform the same task with an added limitation or advantage.

The following variables are to be considered in developing an NDE procedure and choice of method. A planned analysis of task at hand must be made for each test.

- Material manufacturing process
- Level of acceptability desired
- Accessibility of article
- Type and origin of discontinuity
- Cost of testing
- Available equipment for testing.

In the succeeding paragraphs, we will discuss some particle cases and how an evaluation was made based on metallurgical analysis of defects and limitations of various NDE methods.

Defects in weldments

1. Heat-affected zone (HAZ) cracking

This is a weld-related defect related to both ferrous as well as nonferrous welds. The cracks are open to the surface, and they are generally quite deep and often very tight. They are found to run parallel to the direction of weld in the HAZ of the parent metal.

Metallurgical evaluation: Hot cracking of HAZ of weldments increases in severity with the increasing carbon equivalent.

NDE method selection options

- Magnetic particle testing (MT)

  Very useful in detecting and evaluating the HAZ cracks in ferromagnetic material.
- Liquid penetrant testing (PT)

  Normally used for nonferrous weldments.
- Radiographic testing (RT)

  Not normally effective for detecting HAZ cracks.
- Ultrasonic testing (UT)

  The process is utilized where specialized application is developed. Strict acceptance standard is developed for evaluation of HAZ cracks. Sound beam deflection is dependent on factors like sharp versus rounded root radii and slope conditions.
- Eddy current (ET)

  Not normally used for detection of HAZ cracks; the process can be adopted to evaluate HAZ cracks in nonferrous materials.

2. Surface Shrink Cracks

This weld-related defect is common to both ferrous and nonferrous welds. The cracks are open to the surface on the face of the weld, fusion zone, and base metal. The cracks are very small and tight, and they may run both parallel and transverse to the direction of weld.

Metallurgical evaluation: Shrink cracks are the result of improper and localized heating. Localized heating and cooling associated with welding sets up stresses that exceed the tensile strength of the material, causing it to crack. Restriction to expansion and contraction can also set up excessive stresses leading to crack.

NDE method selection options

- Magnetic particle testing (MT)

  Very useful in detecting and evaluating the shrinkage cracks in ferromagnetic material. Magnetizing may be done from different directions to get all cracks.
- Liquid penetrant testing (PT)

  Successfully used for detecting and evaluating shrinkage cracks in nonferrous weldments.
- Radiographic testing (RT)

  Not normally effective for detecting shrinkage cracks.
- Ultrasonic testing (UT)

  The process is not utilized for evaluation of shrinkage cracks, as other NDE methods are capable of doing it at much lower cost.
- Eddy current (ET)

  Not normally used for detection of shrinkage cracks; the process can be used to evaluate shrinkage cracks in nonferrous materials.

3. Inclusions

This is a weld-defect associated with both ferrous as well as nonferrous welds. The inclusions may be open to the surface or subsurface. Inclusions may be metallic or nonmetallic. They may appear singularly or linearly distributed or scattered in the weld. **Metallurgical evaluation:** Metallic inclusions are the particles of metal that have different density, like tungsten inclusion in the gas tungsten arc welding (GTAW) process, or it may be nonmetallic like oxides, sulfides, slag, etc., trapped in the solidifying weld-metal.

NDE method selection options

- Radiographic testing (RT)

  This method is most suitable to detect an inclusion in the weld. They appear as sharply defined, round, erratically shaped, or elongated spots of lighter density on the radiographs. The dense material inclusion will appear lighter than the parent metal density on the film.
- Ultrasonic testing (UT)

  Ultrasonic testing can also detect inclusions as planner discontinuity but will not be able to define if that indication is inclusion or some other discontinuity.
- Magnetic particle testing (MT)

  Not able to detect internal inclusions.
- Liquid penetrant testing (PT)

  Not able to detect internal inclusions.
- Eddy current (ET)

  Not normally used for detection of inclusions in welds except for welds on some applications on thin wall tubing.

4. Lack of Penetration

This is a weld-defect that generally occurs at the root of the weld and running parallel with the weld.

Metallurgical evaluation: Caused by root face of the weld not reaching fusion temperature before weld-metal is deposited. This is also caused by fast weld rate, too large welding rod, or too cold a bead.

NDE method selection options

- Radiographic testing (RT)

  This method is most suitable to detect an inclusion in the weld. They appear as sharply defined, linear indication running in the center of the weld. The indications may be long or intermittent. Good sensitivity and density of the film will ensure proper evaluation.
- Ultrasonic testing (UT)

  Ultrasonic testing can also detect lack of fusion; it will appear on the scope as a definite break and appear as a planner discontinuity but will not be able to define if that indication is inclusion, cracks, or some other discontinuity.
- Magnetic particle testing (MT)

  Not able to detect internal inclusions.
- Liquid penetrant testing (PT)

  Not able to detect internal inclusions.
- Eddy current (ET)

  Not normally used for detection of lack of fusion in welds except for welds on some applications on thin wall tubing.

5. Gas Porosity

This is a weld-defect associated with both ferrous as well as nonferrous welds. The porosity may be open to the surface or subsurface. They may be elongated, round, or teardrop-shaped. They may be clustered or scattered throughout the weld.

Metallurgical evaluation: Porosity in weld is caused by gas entrapment in the molten metal. Too much moisture on the base metal or filler metal or improper cleaning or preheating all may cause and contribute to gas porosity.

NDE method selection options

- Radiographic testing (RT)

  This method is most suitable to detect porosity in the weld. They appear as oval-shaped spots with smoother edges.
- Ultrasonic testing (UT)

  Ultrasonic testing can also detect inclusions as an area of separation.
- Magnetic particle testing (MT)

  Except for surface opening porosity, MT method is not able to detect internal porosity in the welds.
- Liquid penetrant testing (PT)

  Except for surface open porosity, the PT method is not able to detect internal porosity in the weld.
- Eddy current (ET)

  Not normally used for detection of porosity in welds except for welds on some applications on thin wall tubing.

Defects in material caused by manufacturing and service processes

I. **Burst** is a defect associated with processing. It can be found in ferrous and nonferrous wrought material. This is manifest on either the internal or external surface as a straight or irregular cavity, varying in size from wide open to very tight. It is often parallel to the grain of forgings, rolling, or extrusion.

Metallurgical evaluations: Forging bursts are surface or internal ruptures caused by processing at too low a temperature, excessive working, or metal movement during rolling or extrusion operations.

A burst has no spongy appearance and, therefore, is distinguishable from pipe (pipe is also a type of defect), even if it occurs in the center.

Bursts are often large and very seldom healed during subsequent working.

NDE method selection options

1. Ultrasonic method (UT)

Normally used. As the bursts are definite openings in the material exposed or hidden from the surface, they produce a very sharp reflection on the scope.

UT method is capable of detecting variable degrees of burst and condition not detected by other NDE methods.

Limitations:

Other defects like nicks, gouges, raised areas, sharp tool marks, tears, foreign material, or gas bubbles on the material may mask the result.

2. Eddy current testing (ET)

This method is restricted for use on wires, rods, and other articles normally under 0.25-in. diameter, hence not normally used for mass defect evaluation of larger objects.

3. Magnetic particle testing (MT)

Applied to wrought ferromagnetic material in which the burst is open to the surface or has been exposed to the surface. Results are limited to the surface opening or near-surface exposure of burst.

4. Liquid penetrant testing (PT)

The method is limited to evaluation of surface opening bursts, hence the process is normally not used to detect and evaluate defects like burst.

5. Radiography testing (RT)

The variables such as direction of burst, close interfaces, wrought materialist geometry, discontinuity size, and material thickness may be restrictive in effective use of the method. This method is not normally used for detecting and evaluation of burst.

II. Cold Shuts

Cold shuts are produced during casting of molten metal. They are inherent defects found in ferrous and nonferrous cast-material. They are open to the surface or may be subsurface appearing as smooth indentations on the cast surface resembling a forging lap. Cold shuts are the presence of interposing surface films, cold sluggish metal, or any factor that prevents fusion of two meeting surfaces.

Metallurgical evaluation: Cold shuts result from splashing or surging of molten metal, by interrupted pouring, or a meeting of two streams of metal coming from two different directions. They are also caused by solidification of one surface before another metal flows over it. Often found in casting molds that have several spurs or gates.

NDE method selection options

1 Liquid penetrating testing (PT)

This is the primary method to evaluate surface cold shuts in both ferrous and nonferrous materials.

The indications appear as a smooth, regular, continuous, or intermittent line. PT method is best used on metals like nickel-based alloys, stainless steels, and titanium where sulfur and chlorine are limited to 1% maximum.

Sometimes the geometry of the casting may be restrictive in effective application of the PT method. Casting with blind surfaces, recesses, orifices, and flanges many cause difficulty in removal of excess penetrant or allow the developer to build up, thus masking the defect and its evaluation.

2 Magnetic particle testing (MT)

More suitable for use to detect cold shuts in ferromagnetic material. Some duplex structure material that have different magnetic retentively may show indications that are, in fact, not cracks and thus mask or confuse actual openings.

3 Radiographic testing (RT)

Casting configuration is the limiting factor in evaluation of cold shuts in castings. If detected, they appear as dark lines or a band of variable length and width with a definite smooth outline.

4 Ultrasonic testing (UT)

Cast structure and article configuration do not, as a general rule, lend themselves to the UT test method. This method is not recommended.

5 Eddy current testing (ET)

Casting geometry and inherent material variables restrict use of this method. ET is not recommended for use to detect cold shuts in castings.

III. Hot tears

Hot tears are the ruptures often associated with castings. They are the result of stresses developed due to uneven cooling of material. They may be internal or appear near the surface as a ragged line of variable width and numerous branches. The tears may be single or in groups.

Metallurgical evaluation: Hot tears are cracks that are caused by the stresses developed by uneven cooling while the material is still in a brittle state. The tears are often at the point where the temperature gradient is abrupt, raising the possibility of more stresses. Such locations could be the junction of a thicker section with a relatively very thin section of the casting.

NDE method selection options

1 Radiographic testing (RT)

Because the material structure is cast and the tears may be internal, the method of choice is radiography testing. However, the sensitivity of the radiograph and also the orientation of defect to the radiation beam could be limiting factors.

2 Magnetic particle testing (MT)

Hot tears that are exposed to the surface of near the surface can be detected by the MT method. Magnetizing in different orientation may be a challenge in some cases. Precleaning the surface is very essential for successful results.

A testing procedure that includes a combination of MT and RT must be developed in which MT may be sued to screen out surface defects, and RT may be used to detect internal tears.

3 Liquid penetrating testing (PT)

Nonferrous material casting may be tested with PT in place of MT. PT method will be able to detect only the surface opening hot tears. Absorption of penetrant in the openings may be a cause of concern for the next stage of processing.

4 Ultrasonic testing (UT)

Cast structure and article configuration do not, as a general rule, lend themselves to UT test method. This method is not recommended.

5 Eddy current testing (ET)

The metallurgical structure of casting as well as the complex configuration of the castings will not allow for proper detection or evaluation. This method is not recommended.

IV. Microshrinkage

Microshrinkage is specific to magnesium casting; this is an internal defect appearing as voids in the grain boundaries.

Metallurgical evaluation: Microshrinkage is caused by the withdrawal of low melting constituents from the grain boundaries. Shrinkages occur when metal is in a plastic or semimolten stage. If sufficient molten metal cannot flow into the molds while casting is in a cooling stage, the shrinkages would leave a void. These voids are identified by their appearance and by the time in the plastic stage when it occurs.

NDE method selection options

1 Radiographic testing (RT)

Radiography is the most effective method, and it is capable of determining the acceptable level of microshrinkages.

On the radiograph, it appears as dark uneven patches or an elongated swirl resembling streaks. They are indications of cavities in the grain boundaries.

2 Liquid penetrating testing (PT)

Used on the finished and machined products, microshrinkages are normally not open to the surface. On cut or machined portion, the defects appears as hairline cracks or even as a large open porous indication.

3 Eddy current testing (ET)

Not recommended, as the casting configuration and type of discontinuity do not lend themselves to this method.

4 Ultrasonic testing (UT)

Cast structure and article configuration do not, as a general rule, lend themselves to UT test method. This method is not recommended.

5 Magnetic particle testing (MT)

Material is not ferrous, hence this method is not applicable.

V. Unfused porosity

This is an internal defect caused during processing and associated with rolled, forged, or extruded wrought aluminum. These are very thin fissures aligned with the flow of grains.

Metallurgical evaluation: This defect is often associated with cast ingots. During a subsequent process like rolling, forging, or extrusion process, these are flattened into very thin shape. If the internal surfaces of these discontinuities are oxidized or have inclusions, then they do not fuse during the subsequent processes and appear as very fine voids.

NDE method selection options

1 Ultrasonic testing (UT)

This method is extensively used as the most successful method to detect unfused porosity. UT method determines the 3D locations of the defect.

2 Liquid penetrating testing (PT)

This method is used on nonferrous material where the defect is open to the surface.

3 Eddy current testing (ET)

Normally not used.

4 Radiographic testing (RT)

Thin openings are difficult to detect by this method, hence this method is normally not used.

5 Magnetic particle testing (MT)

Because the material is nonmagnetic, this method is not used.

VI. Fillet Cracks

This is a service category defect of ferrous as well as nonferrous material. The defect is open to the surface at the junction of the bolt head to shank (fillet). The fillet crack originates outside and progresses inward.

Metallurgical evaluation: The crack is caused at stress riser points like the sharp change in the diameter as noted in the head to shank transition in a bolt. During the service life of a bolt, repeated loading takes place whereby the tensile load fluctuates in magnitude. These loads can cause fatigue failure starting at the point where the stress rises occur. Fatigue failures are a surface phenomenon; they start at the surface and propagate inward.

NDE method selection options

1 Ultrasonic testing (UT)

Extensively used, a wide selection of transducers and equipment enable on-the-spot evaluation for fillet cracks.

2 Liquid penetrating testing (PT)

Frequently used during maintenance and overhaul process. Indications are very sharp and clear.

3 Magnetic particle testing (MT)

Possibility to use is limited to ferromagnetic materials.

4 Eddy current testing (ET)

Not normally used.

5 Radiographic testing (RT)

Not used.

VII. Grinding Cracks

These are associated with heat-treated, case-hardened, chrome-plated, or ceramic materials. This is a processing defect on the surface of ferrous or nonferrous metal. They appear at a right angle to the direction of grinding. They appear as shallow and sharp at root, often resemble heat-treat cracks, but may appear in a group.

Metallurgical evaluation: These are thermal cracks often developed by local overheating of the surface being ground. Grinding of hardened surfaces often develop cracks. Use of proper coolant may prevent some of these cracks. Excessive feed during grinding or too heavy cut can cause such cracks.

NDE method selection options

1 Liquid penetrating testing (PT)

Because these are surface opening defects, there are easily detected by PT method. PT method is especially suitable for nonferrous material. Because there are very tight and fine cracks, they require extra dwell time for the penetrant.

2 Magnetic particle testing (MT)

The method is used on ferrous material with a similar effect as PT on nonferrous materials. Because these cracks are often at right angle to the direction of grinding, the orientation of the magnetic field assumes importance.

3 Eddy current testing (ET)

Normally not used, however, this method can be adopted for use on specific nonferrous materials.

4 Ultrasonic testing (UT)

Not used as other methods are more effective and can be done at low cost.

5 Radiographic testing (RT)

Method is less likely to detect these fine cracks. Method is not recommended.

VIII. Thread cracks

This is a crack that develops in service. This is noted on both ferrous and nonferrous material.

Metallurgical evaluation: These cracks start at the root of the thread and are transgranular (transverse to the grain). These are fatigue cracks, often caused by cyclic stresses resulting from vibrations, flexing, or a combination of both at the stress risers at the root of the thread. They may start as small microscopic discontinuities and propagate in the direction of applied stress.

NDE method selection options

1 Liquid penetrating testing (PT)

PT is the most effective method for nonferrous as well as ferrous materials. The fluorescent penetrant method is most effective. Cleaning of the thread is important as low surface tension liquids are not effective cleaners.

2 Magnetic particle testing (MT)

Equally effective method but limited to ferromagnetic material. The thread configuration may present nonrelevant indications that may make interpretation difficult.

3 Eddy current testing (ET)

Not normally used, however, specially adopted equipment for specialized use can be developed.

4 Ultrasonic testing (UT)

The process is not suitable for this type of work.

5 Radiographic testing (RT)

Not recommended. Other less-cost and more-effective methods are best suited for this kind of work.

IX. Tubing cracks

This is an inherent defect of nonferrous tubes found in the internal (ID) surface of drawn tubes. These cracks are found parallel to the direction of grain flow.

Metallurgical evaluation: There can be several causes working individually or in combination that can contribute to these cracks. These causes may be one or a combination of improper cold reduction, imbedded foreign material during cold working, or insufficient heating during annealing.

NDE method selection options

1 Eddy current testing (ET)

Eddy current method is most suitable to detect this type of defect in tubing. Small-bore tubing with low wall thickness can be covered by this method.

2 Ultrasonic testing (UT)

A wide verity of equipment and transducers are available to use this method. UT method may be limited by the temperature that the transducers can work, if inspection is required on a hot-tube. Selection of sulfur-free couplant may be required on some material like high-nickel alloys.

3 Radiographic testing (RT)

Discontinuity orientation and thickness are the limiting factors; this method is not generally used.

4 Liquid penetrating testing (PT)

Not recommended.

5 Magnetic particle testing (MT)

Not applicable as the materials are nonmagnetic.

X. Hydrogen Flake

These are process-related internal fissures that occur in ferrous material. Often found in steel forgings, billets, and bars.

Metallurgical evaluation: The flakes appear as bright silvery areas on a fractured surface. If etched, they appear as short discontinuities. In machined surface, they appear as hairline cracks. Flakes are very thin and align parallel with the grain.

NDE method selection options

1 Ultrasonic testing (UT)

Most effective method and used extensively. The surface condition can determine if the material can be screened using either immersion or contact method. On an A-scan presentation, hydrogen flakes will appear as hash on the screen or loss of back wall reflection.

Surface cleaning removal of loose scale, dirt, oil, and grease is essential for proper inspection. Other irregularities arising from gouging, tool marks, scarfing, etc. may mask the interpretation as back wall; they all cause loss of back wall reflection.

2 Magnetic particle testing (MT)

Possible to use on finished machined surfaces. Flakes appear as short discontinuity and resemble chrome checks or hairline cracks.

3 Liquid penetrating testing (PT)

The discontinuities are very tight and small making it difficult to detect by this method, hence this method in not used.

4 Eddy current testing (ET)

The metallurgical structure of the material limits the use of this method.

5 Radiographic testing (RT)

Not recommended, as the size and orientations present limitation to the RT method.

XI. Lamination

Laminations can be found in both ferrous and nonferrous wrought material, like forgings, extrusions, and rolled material. They can be found both on the surface as well as internal. They are extremely thin and generally aligned parallel to the work surface of material. They may contain thin film of oxide between the surfaces.

Metallurgical evaluation: Laminations are separations or weaknesses generally aligned parallel to the work surface of the material. They are caused when blister, pipe, seams, inclusions, or segregations are elongated and made directional by working. Laminations are flattened impurities that are extremely thin.

NDE method selection options

1 Ultrasonic testing (UT)

This is the most suitable method to detect most of the laminations. The use of various wave modes and angle probes in immersion or contact process may be used to detect lamination on various geometrics of material. They appear as definite loss of back wall echo. For very thin sections, thorough transmission and reflection techniques may be more effective. The UT method can plot out the size and depth of the lamination

2 Magnetic particle testing (MT)

The surface opening ends of lamination may be detected by the MT method on ferromagnetic material. Lamination will appear as a straight line of intermittent linear indications.

3 Liquid penetrating testing (PT)

Method is suitable for use on nonferrous material. The method has a similar effect and limitations as magnetic particle method.

4 Eddy current testing (ET)

Not practical for use.

5 Radiographic testing (RT)

Not recommended due to the orientation of lamination, which is less likely to be resolved on RT film.

XII. Laps and Seams

This is a surface defect caused during processing and is associated with both ferrous and nonferrous material.

Laps are found in wrought forgings, plates, tubing, and bars. Laps appear on the surface as wavy lines. Usually laps are not very pronounced. They are often tightly adherent because they enter the surface at a small angle. Often, their surface opening is smeared closed. Laps or rolled threads are most common examples of such defects. Laps and seams appear on the surface as wavy lines, often quite deep and sometimes very tight, appearing as hairline cracks.

Seam are surface defects associated with rolled rods and tubing. They are long, often quite deep, and sometimes very tight. They often occur in parallel fissures with grain and at times spiral.

Metallurgical evaluation: Seams originate from blowholes, cracks, splits, and tears discussed earlier. These are elongated in the direction of rolling or forging. The distance between adjacent interfaces of the discontinuity is very small.

Laps are similar to seams, and they can occur in any part of the material. They often result from improper rolling or sizing operations. During the processing of the material, corners may get folded over or an overfill may exist during sizing. These would result in material being flattened but not fused into the surface.

NDE method selection options

1 Magnetic particle testing (MT)

This method is compatible with both ferrous and nonferrous material. The indications may appear as straight, spiral, or slightly curved. They may be an intermittent or continuous indication. Both laps and seams may appear as individual or cluster indication. Magnetic buildup at laps and seams is very small, hence larger than usual magnetizing current is applied.

In forgings, the orientation of laps may lie in a plane that is nearly parallel to the surface.

2 Liquid penetrating testing (PT)

This method is applicable to nonferrous material. Laps and seams may be very tight to be detected by PT method. Application of fluorescent penetrant is the most preferred and successful method.

3 Ultrasonic testing (UT)

A limited application of UT is possible for testing material prior to machining wrought material. Surface-wave technique permits accurate evaluation of depth and area of the defect. Definite loss of echo between the inner faces of laps and seam is shown on the screen.

4 Eddy current testing (ET)

This method is used for evaluation of laps and seams in tubes and pipes. Material configuration and size are the limiting factors in extensive use of this method.

5 Radiographic testing (RT)

RT method is not recommended for detecting laps and seams.

XIII. Hydrogen Embrittlement

This is a surface discontinuity associated with ferrous material. The defects are caused by both service conditions as well as processing conditions. These are small non-dimensional (interface) with no orientation or direction. Often associated with material exposed to free hydrogen or subject to pickling or plating.

Metallurgical evaluation: Operations like pickling, electroplating, and cleaning prior to electroplating generates hydrogen at the surface of the material. This hydrogen penetrates the surface of the material creating immediate or delayed cracking called hydrogen embrittlement.

NDE method selection options

1 Magnetic particle testing (MT)

Indications often appear as a fractured pattern; hydrogen embrittlement cracks are randomly oriented and can be often aligned with magnetic field. MT test must be carried out both before and after plating operation.

2 Liquid penetrating testing (PT)

Not normally used for hydrogen embrittlement crack detection.

3 Ultrasonic testing (UT)

Method is not suitable to detect this type of crack.

4 Eddy current testing (ET)

Not recommended for detecting these cracks.

5 Radiographic testing (RT)

Not capable of detecting hydrogen embrittlement cracks.

Corrosion-related defects and their detection

A. Intergranular Corrosion (IGC)

This is an external as well as internal-occurring defect. IGC is a service condition-related defect; it can also develop during service due to the faulty fabrication process. This is exclusively a nonferrous material defect. The defect manifests itself as a series of small micro-openings with no definite pattern. They may appear singularly or in groups. If IGC appears on the surface then, in most cases, it is too late to save the material. As the name suggests, it is intergranular and follows the grain boundaries of the material.

Metallurgical evaluation: Factors that contribute to IGC are: (a) unstabilized austenitic stainless steel or (b) improper heat treatment, generally solution annealing. Any of these two conditions can cause IGC during the service life of the material.

NDE method selection options

1 Liquid penetrating testing (PT)

This is the best-suited method for detection of IGC in material. Selection of chlorine-free and chlorine-emitting cleaning product is essential.

2 Radiographic testing (RT)

In more advanced conditions of IGC, radiography may be able to detect the cracks. Correct location of the defect on the film and sensitivity of the film may be a problem.

3 Eddy current testing (ET)

ET method can be used as a screening method of tubes and pipes.

4 Ultrasonic testing (UT)

Not normally used, as the method is not suitable for detecting such cracks.

5 Magnetic particle testing (MT)

Not applicable as material is nonmagnetic.

B. Stress Corrosion Cracks (SCC)

This is a service condition-related defect occurring in both ferrous and nonferrous material.

They are often very deep and often follow the grain flow; however, transverse cracks are also possible.

Metallurgical evaluation: For stress corrosion to occur, the following three phenomena must coexist: (1) a sustained static tensile stress; (2) presence of corrosive environment; and (3) use of material that is susceptible to this type of failure. Stress corrosion is most likely to occur in a high level of stress than low levels of stress. The stresses include residual stresses and applied stresses.

NDE method selection options

1 Liquid penetrating testing (PT)

Most common method to use for the detection of stress corrosion cracks, especially on nonferrous materials.

2 Magnetic particle testing (MT)

MT is mostly used on ferrous material, for similar results as the PT method.

3 Eddy current testing (ET)

Eddy current testing is capable of resolving some SCC indications depending if the configuration is compatible with the equipment.

4 Ultrasonic testing (UT)

Because the discontinuity orientation is mostly perpendicular to the surface, surface-wave technique may be required, but it would limit the results and increase the cost of inspection.

5 Radiographic testing (RT)

Not suitable to detect SCC in most cases.

Ferrite testing

9

Effect of ferrite in austenitic welds

Weld deposit that is fully austenitic has a tendency to develop small fissures; this is possible even under a condition of minimum stress. These small fissures tend to locate transverse to the weld fusion line in weld passes and base material that was reheated to near-melting point of the material by subsequent weld passes.

The effect of these microfissures is not well established on the performance of the weldments, because it is clear that the tough austenitic matrix blunts the progression direction of these fissures. Several fissure-containing weldments are recorded to exist and have performed satisfactorily under severe conditions. However, the very tendency to develop fissures goes hand in hand with the development of possible larger cracks that can cause catastrophic failures. This possibility of failure has motivated development of a process that would reduce or eliminate chances of microfissures.

It is established that the presence of a small fraction of magnetic delta ferrite phase in an otherwise austenitic weld deposit has a pronounced influence in the prevention of both centerline cracking and fissuring. Both the presence and amount of delta ferrite in an as-welded material is largely influenced and dependent on the composition of the weld-metal. The balance between the ferrite-forming and austenite-forming elements is the key to the presence of δ ferrite. The most common ferrite- and austenite-forming elements are listed in Table 3-9-1. The details on the subject are discussed with the help of DeLong and Schaeffler's diagrams in Section 2 "Welding Metallurgy" of this book.

Having learned about the advantages of having δ ferrite in a weld, we must also note that an excessive amount of ferrite is also not desirable in welds, as it lowers the ductility and toughness of the weld-metal. Delta (δ) ferrite is also preferentially attacked by a corrosive environment. It is also attacked in a sensitizing range of the temperature between 800°F and 1600°F (425°C and 870°C). In this temperature range, ferrite tends to transform in part to a brittle intermetallic compound called sigma phase that severely embrittle the weldments.

This requires that the level of ferrite in austenitic weldments must be controlled. This is done by metallographic examination of the specimen and volume percent ferrite present is determined. This method is not very favored for several reasons; one of

Table 3-9-1 Ferrite forming and austenite forming elements.

Ferrite-forming elements	Austenite-forming elements
Chromium	Nickel
Silicon	Manganese
Columbium	Carbon
Molybdenum	Nitrogen

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them is that the distribution of ferrite in the weld-metal is not uniform, and the sample preparation procedure method is very tedious. The effect of the faulty result is too serious to risk such a method.

Chemical analysis of weld-metal and its analysis result with constitution diagrams like Schaeffler and DeLong is very common and popular in use. The result of this method is dependent on the accuracy of the analysis.

As ferrite is magnetic, it can be measured by magnetic responses of the austenitic material. This measurement is reproducible in laboratories if standard calibrated equipment is used. Most of the instruments are able to convert the magnetic force reading to a standard ferrite measurement.

Ferrite content has traditionally been expressed in volume percent in the weld-metal until ferrite number (FN) was recommended. Because there is no agreement in laboratories on reporting of absolute ferrite percentage, an arbitrary FN system was developed for reporting. American Welding Society (AWS) has developed a scale described in AWS 4.2-74, Standard Procedure for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld-Metal. The FN scale, although arbitrary, approximates the true volume percentage of ferrite at least up to 10 FN.

The ferrite content recommended in weld filler metal is usually between 3% and 20%. A minimum of 3% ferrite is desirable to avoid microfissuring in welds. The upper end of 20% ferrite is required when needed to offset dilution losses in weld-metal. Delta (δ) ferrite verification can be made by test on undiluted weld deposits using magnetic measuring devices. AWS 5.4 details the procedure for preparation of pads for ferrite measurement.

The testing of ferrite in a laboratory setting is a very different from the portable ferrite indicators used in the field sites; in some cases, the details and results can vary significantly from the two methods or onsite use.

Pressure testing

10

Purpose

Pressure tests are carried out to induce a predetermined stress level by pressurizing the equipment and observe the performance.

Leak test is carried out to determine the extent of flaw's depth, that is, to ensure if the flaws in the material or weld extend to the surface of the material. The test can be either simple pressurizing to a relatively low pressure to create a pressure differential and visually inspecting for leaks or as sophisticated methods for use on electronic equipment like acoustic emission, etc., to detect possible cracks and their growth over time.

Method

In its simplest form, the test is carried out by increasing the internal pressure and creating a pressure differential with ambient pressure. This allows the liquid to flow out of possible openings, i.e., the leak. This is inspected by visual methods.

In case fluorescent dyes are used, the inspection is carried out in a dark place and use of black (ultraviolet) light is required.

If the test media used is air or gas, then the leaks are located by looking for rising bubbles from the test surface as an emulsion of mild soap and water is applied on the test surface.

Sometimes pressurized components are immersed in water to detect leak locations.

Test medium

The media used for leak testing can be any liquid that is nonhazardous to personnel or environment. Water is the most common medium for testing. Light oils are also used as a test medium. When water or any other liquid is used as a medium for testing, it often called hydrotesting. A typical pipeline hydrotest is discussed at the end of this chapter.

Some tests require use of air or gas. Gas test is very sensitive in detecting small leaks, but both air and gas as test mediums are used with utmost care as they have an inherent disadvantage of an explosive-like effect in the event of failures.

Sensitivity of the test

The test can be made more effective and sensitive by use of lighter chemicals, gases, or fluorescent dyes added to the water.

The degree of sensitiveness is adjusted with the required degree of flaw detection and relative degree of cost and risk involved in testing.

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Proof testing

Proof test is a relatively high-pressure test compared with the leak test. Proof test is carried out to determine if the system can withstand applicable service loadings without failure or acquire permanent deformation in the part.

Proof test is generally designed to subject the material to stresses above those that the equipment is expected to carry in service. Such service stress is always below the yield strength of the material of construction. In this respect, also read the discussion on hydrotest of a pipeline at the end of this chapter.

The methods of these tests vary according to the specific design and requirements of the service. Mostly, the proof test is applied in connection with visual inspection. These specific requirements are generally specified in the project specification or dictated by the code of construction.

The test media is usually water (hydrostatic test) or air (pneumatic test), which is ordinarily used for relatively low pressure because of the inherent safety associated with compressed air.

Hydrostatic testing has been used to determine and verify pipeline integrity. Innumerable information can be obtained through this verification process; however, it is essential to identify the limits of the test process and obtainable results. There are several types of flaws that can be detected by hydrostatic testing:

- Existing flaws in the material
- Stress corrosion cracking (SCC) and actual mechanical properties of the pipe
- Active corrosion cells
- Localized hard spots that may cause failure in the presence of hydrogen, etc.

There are some other flaws that cannot be detected by hydrostatic testing, for example, subcritical material flaws cannot be detected by hydrotesting, but the test has a profound impact on the posttest behavior of these flaws.

The process of proof testing involves the following steps.

- The proof test involves pressurizing the vessel or pipe with water to a stress level above the design pressure but below the yield strength of the material of construction.
- Hold the pressure to the required time.
- Monitor for the drop in pressure.
- Inspect the object for any leak while it is under the test pressure.
- Controlled depressurizing.

Vessels or pipe section pressurized with air are often inspected with application of emulsified soap and inspected for rising bubbles from the leak locations. Sometimes, pressurized components are immersed in water to detect leak locations.

Practical application of hydrostatic testing

Hydrostatic testing is used to determine and verify pipeline integrity. There are several data that can be obtained through this verification process; however, it is essential to identify the limits of the test process and obtainable results. There are several types of flaws that can be detected by hydrostatic testing such as SCC and actual mechanical properties of the pipe, compared with some other flaws that cannot be detected by hydrostatic testing, for example, subcritical but active corrosion cells, localized hard spots that may become cause of failure in the presence of hydrogen, etc.

Given that the test will play a significant role in the nondestructive evaluation of pipeline, it is important to utilize the test pressure judiciously.

The maximum test pressure should be so designed that it provides a sufficient gap between the test pressure and the maximum operating pressure (MOP), in other words:

The maximum test pressure shall be $> {}^{\mathrm{Gap}}\mathrm{MOP}$.

This also presupposes that, after the test, the surviving flaws in the pipeline shall not grow when the line is placed in service at the maintained operating pressure. For setting the maximum test pressure, it is important to know the effect of pressure on the growth of the defect. Also consider how these growths would be affected by pressure over the time; these defects are often referred to as subcritical defects because these will not fail during a one-time high-pressure test but would fail at lower pressure if held for longer time. The size of discontinuity that would be in the subcritical group will be those that would fail independent of time at about 105% of the hold pressure. This implies that maximum test pressure would have to be set to at least 5%–10% above the MOP to avoid growth of subcritical discontinuities during the operation life of a pipeline.

The phenomenon of pressure reversal occurs when a defect survives a higher hydrostatic test pressure, but it fails at lower pressure in a subsequent repressurization. One of several factors that work to bring this phenomenon is the creep-like growth of subcritical discontinuities over time at lower pressure. The reduction in the wall thickness in effect reduces the discontinuity depth to the material thickness (d/t) ratio. This increase in d/t ratio in effect reduces the ligament of the adjoining defects, which in effect reduces the required stress to propagate the discontinuity. The other factor affecting the pressure reversal is that the damage to the Crack Tip Opening (CTO), as the CTO is subject to some compressive force leading the crack tip to force-close. This facilitates the growth of the crack upon repressurization to a much lower pressure. Hence, if such pressure cycle is part of the design, then pressure reversal is a point of consideration.

When a pipeline is designed to operate at a certain MOP, it must be tested to ensure that it is structurally sound and can safely withstand the internal pressure before being put into service. Generally, gas pipelines are hydrotested by filling the test section of pipe with water and pumping the pressure up to a value higher than MAOP and holding it at this pressure for a period of 4–8 h. The magnitude of test pressure is specified by code, and it is usually 125% of the operating pressure. Thus a pipeline designed to operate continuously at 1000 psig will be hydrostatically tested to a minimum pressure of 1250 psig.

Let us consider a pipeline NPS 32, with 12.7-mm (0.500-in.) wall thickness, constructed of API 5L X 70 pipe. Using temperature-derating factor of 1.00, we calculate the MOP of this pipeline from the following:

$$\mathrm{P} = \{2 \times \mathrm{t} \times \mathrm{SMYS} \times 1 \times \mathrm{factor}\,(\mathrm{class1}) \times 1\}/\mathrm{D} \qquad [1]$$

Substituting the values:

$$2 \times 0.5 \times 70{,}000 \times 1 \times 0.72 \times 1/32 = 1575\,\text{psig}$$

The same pipeline, if designed to factor of 0.8, this pressure will be 1750 psig.

If the fittings are of ANSI 600 then the maximum test pressure will be $(1.25 \times 1440^{(\text{ASME B 16.5})})$ 1800 psig.

If however ANSI 900 fittings were chosen, the pressure would be $(1.25 \times 2220^{(\text{ASME B 16.5})})$ 2775 psig.

If the selected design factor is for class one location, then the factor would be 0.72; in this case, the test would result in the hoop to reach 72% of the specified minimum yield strength (SMYS) of the material. Testing at 125% of MOP will result in the hoop stress in the pipe to a value of $1.25 \times 0.72 = 0.90$ or 90% of SMYS. Thus, hydrotesting the pipe at 1.25 times the operating pressure, we are stressing the pipe material to 90% of its yield strength that is 50,400 psi (factor $0.72 \times 70{,}000$).

If, however, we use design factor of 0.8 as is now often used, and allowed by several industry codes, testing at 125% of MOP will result in the hoop stress in the pipe to $1.25 \times 0.8 = 1$. The hoop stress would reach to 100% of the yield strength (SMYS). So, at the test pressure of 1800 psig, the S_h (Hoop Stress) will be 56,000 psi ($0.8 \times 70{,}000$). This will be acceptable in case of class 600 fittings are the limiting factor.

But if the class 900 fittings were taken in account as limiting the test pressure, then the maximum test pressure would be (1.25×2220) 2775 psig, and the resulting stress would be 88,800 psi, which will be far above the maximum yield stress of API 5L X 70 PSL-2 material.

Critical flaw size

Using a test pressure at 100% of the material yield strength has some important preconditions attached to it. Such test pressure would require that the acceptable defect size be reassessed. All else being equal, a higher design factor resulting in thinner wall (d/t) will lead to a reduction in the critical dimensions of both surface and through-wall defects. Critical surface flaw sizes at design factors of 0.80 and 0.72, flow stress dependent will also be dependent on the acceptable Charpy energy for the material and weld.

As stated in the earlier discussions, this increase in d/t ratio in effect reduces the ligament of the adjoining defects, which in effect reduces the required stress to propagate the discontinuity. Critical through-wall flaw lengths are also factors to be assessed; although there is a modest reduction in critical flaw length, it still indicates very acceptable flaw tolerance for any practical depth, and the reduction will have negligible influence in the context of integrity management. Note that flaws deeper than about 70% of wall thickness will fail as stable leaks in both cases. This statement implies that mere radiography of the pipe welds (both field and mill welds) will not suffice; automatic ultrasonic test (AUT) of the welds will be better suited to properly determine the size of the planer defects in the welds. Similarly, the use of AUT for assessing the flaws in the pipe body will have to be more stringent than usual.

Section 4

Codes and Standards

Introduction

1

There are many codes and standards of interest to a welding engineer. The choice would be on what type of the project is at hand. This is an introduction to some of the codes and specifications in common use in general engineering and oil and gas and petrochemical industries. They also find their applications in various other industries.

Historically, incidents of pressure vessel, bridges failures, notably of steam boilers, and industrial accidents led to the development of regulatory codes. These codes relate to the safety of men and material through design and inspection with awareness of the environment and damage these failures and accidents cause to the environment. The emphasis on safety has comprehensively integrated concerns with damage to environment.

At the end, a list of some very commonly used specifications and their sources are listed, and interested personnel may approach the source to obtain them.

It may, however, be noted that the bodies that issue industrial specifications and the national codes have a very exhaustive list of fields that they address and, as a result, the number of topics they address and the specifications they issue are exhaustive too. It is not possible for a book to cover even a small fraction of them. In this book, an attempt is made to introduce some of them so that an introduction is made and a way is available for the readers to explore through the specification issuing body's web addresses and refer any specific publication that may be of specific intent.

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Codes, specifications, and standards

2

American National Standards Institute (ANSI; http://www.ansi.org) and American Society of Mechanical Engineers (ASME; http://www.asme.org) are the governing organizations for many documents relating to material selection. Similarly, American Society for Testing and Materials (ASTM; http://www.astm.org) is the primary source of specifications relating to various materials (metals and nonmetals), test methods, and procedures including, for example, corrosion-resistant materials and various kinds of mechanical and corrosion tests.

Specifications issued by various institutions including both ASME and ASTM are adopted as part of ANSI.

Specifications are documents legally prescribing certain requirements as to composition, mode of manufacture, and physical and mechanical properties. Standards are documents representing a voluntary consensus. However, when these specifications are adopted by a regulatory authority, they become a code, such as boiler and pressure vessel code (ASME), national building codes, etc.

The National Association of Corrosion Engineers (NACE; http://www.nace.org) has committees that write standards and exchange information in specific industries or particular areas of concern. NACE standards consist of recommended practices, materials requirements, and test methods for a variety of corrosion control or material selection challenges.

In the following paragraphs, we will try to get an introductory perspective on some of the key institutions through their historical developments.

It may be noted that, however exhaustive a list one may prepare, practically it cannot cover all relevant specifications, recommended practices, or recommendations that various bodies around the world have developed over the years and continue to develop. The best way to use this wealth of resources is to refer to one directly related to the subject you are looking for; within that specification, there will be additional references to related subjects and one can follow any of those specific documents that are cross-referenced within the main specification. This general statement applies to nearly all the documents discussed in this list.

American Society of Mechanical Engineers (ASME)

Located at 3 Park Avenue, New York, NY 10016-5990 (http://www.asme.org/), an introduction to ASME would be incomplete without the following words of Bruce Sinclair, an American historian.

"The Society's history helps to reveal the outlines and consequences of a complex technological information-processing system. It is an article of faith that Americans

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are inventive people. But besides machines, they also created a welter of interrelated institutions to translate technical knowledge into industrial practice, and that may have been one of the country's most successful inventions."

Background and history

The 19th century America through the eyes of a mechanical engineer

ASME was founded in 1880 by prominent mechanical engineers, led by Alexander Lyman Holley (1832–82), Henry Rossiter Worthington (1817–80), and John Edson Sweet (1832–1916). Holley chaired the first meeting, which was held in the New York editorial offices of the "American Machinist" on February 16, 1880, with 30 people in attendance. On April 7, a formal organizational meeting was held at Stevens Institute of Technology, Hoboken, New Jersey, with about 80 engineers—industrialists, educators, technical journalists, designers, shipbuilders, military engineers, and inventors.

The later part of 19th century witnessed the widespread establishment of schools and institutions in engineering. Engineers of the day moved easily among the concerns of civil, industrial, mechanical, and mining engineering, with less distinction among them. Many groups were seeking to create organizations of specialized professional standing. But for mechanical engineers, none were devoted to machine design, power generation, and industrial processes to a degree that was capable of projecting a broader national or international role to advance technical knowledge and systematically facilitate a flow of information from research to practical application.

The Institution of Chartered Mechanical Engineers had been successfully established in England 33 years earlier in 1847. In the United States, the American Society of Civil Engineers had been active since 1852, and the American Institute of Mining Engineers had been organized in 1871. Holley had been vice-president of one and president of the other.

Mechanical engineers practiced in industries such as railroad transportation, machine tools, steel making, and pumping. In 1880, there were 85 engineering colleges throughout the United States, most of them offering a full mechanical engineering curriculum with a degree in mechanical engineering.

The first annual meeting was held in early November 1880. Robert H. Thurston, professor of mechanical engineering at Stevens Institute and later Cornell, was the first president. Thurston is credited to have established the first model mechanical engineering curriculum and laboratory.

This was an era of steel power that drove the technology of the day: locomotives, ships, factory machinery, and mine equipment. The Corliss engine and the Babcock & Wilcox water-tube boiler were in their prime. The first real US central power plant—Thomas Edison's Pearl Street Station in New York City—ushered in the era of great electric utilities in 1882. Internal combustion was not far from application. Conglomerates such as US Steel were formed. Industrial research laboratories, such as those at General Electric, du Pont, and Eastman Kodak, proliferated.

The early 20th century

ASME formed its research activities in 1909, devoting their efforts in areas such as steam tables, the properties of gases, the properties of metals, the effect of temperature on strength of materials, fluid meters, orifice coefficients, etc.

Since its inception, ASME has led in the development of technical standards, beginning with the screw thread and now numbering more than 600 specifications. The Society is best known, however, for improving the safety of equipment, especially boilers and for good reason. If we review the archives of engineering, we will note that between the periods 1870 and 1910, at least 10,000 boiler explosions in North America were recorded. By 1910, the rate jumped to 1300–1400 a year. Some were spectacular accidents that aroused public outcries for remedial action. A Boiler Code Committee was formed in 1911 that led to the Boiler Code being published in 1914–15 and later incorporated in laws of most US states and territories and Canadian provinces.

By 1930, 50 years after ASME was founded, the Society had grown to 20,000 members, although its influence on American workers is far greater. Just as the 19th-century railroad created towns and cities along its paths, its interlocking schedules led to establishment of the present time zones. Twentieth-century ASME leaders, such as Henry Robinson Towne, Fredrick W. Taylor, Frederick Halsey, Henry L. Gantt, James M. Dodge, and Frank and Lillian Gilbreth, pioneered management practices that brought worldwide reform and innovation to labor-management relations. Precision machining, mass production, and commercial transportation opened the nation and then the world to American enterprise.

The diversity of mechanical engineering can be seen in ASME's 36 Technical Divisions (plus 1 subdivision) and 3 Institutes. Today's structure of Technical Divisions was established in 1920, when eight Divisions were created.

The primary divisions were

1 Aerospace
1. Fuels
2. Management
3. Materials
4. Materials Handling Engineering
5. Power
6. Production Engineering
7. Rail Transportation

Two more were added next year.

1. Internal Combustion Engine
2. Textile Industries

The most recent addition in June 1996 is the division called

1 Information storage and processing systems division

Present day ASME

In present times, ASME is a worldwide engineering society focused on technical, educational and research issues. It has 125,000 members, conducts one of the world's largest technical publishing operations, holds some 30 technical conferences and 200 professional development courses each year, and sets many industrial and manufacturing standards.

Under the sponsorship of the ASME, the Boiler and Pressure Vessel Committee established rules of safety governing the design, fabrication, and inspection during construction of boilers and pressure vessels. ASME is made up of various committees. There are several Codes, and subcommittees develop these Codes. The fabrication codes include:

List of all 12 ASME boiler and pressure vessels codes

Section I, Power Boilers
Section III, Nuclear Codes
Section IV, Heating Boilers
Section VIII, Division 1 and 2, Pressure Vessels
Section X, Fiberglass Reinforced Vessels.

There are also reference codes issued to support the construction codes. These include:

- Section II, Materials
  - Part A, Ferrous Materials
  - Part B, Non Ferrous Materials
  - Part C, Welding Materials
  - Part D, Materials Properties
- Section V, NDE
- Section IX, Welding Qualifications

Following is a brief discussion about some key ASME specifications and their roles in design and construction of pressure vessels. The key difference in ASME Section VIII Division 1, Division 2, and Division 3 are given in Table 4-2-1.

ASME Section VIII, Division 1 (pressure vessels)

The organization of Section VIII, Division 1 is as follows:

1.	Subsection A	General requirements
	Part UG	General requirements for all methods of construction and all requirements
2.	Subsection B	Methods of Fabrication
	Part UW	Fabricated by welding
	Part UF	Fabricated by forging
	Part UB	Fabricated by brazing
3.	Subsection C	Materials
	Part UNC	Carbon steel
	Part UNF	Nonferrous
	Part UHA	High-alloy steel
	Part UCI	Cast iron
	Part UCL	Cladding and weld overlay
	Part UCD	Cast ductile iron
	Part UHT	Heat-treated ferritic steels
	Part ULW	Layered construction
	Part ULT	Low-temperature materials
4.	Mandatory Appendices	(Indicated by numbers)
5.	Nonmandatory Appendices	(Indicated by letters)

Table 4-2-1 A brief discussion on ASME Section VIII Div. 1, Div. 2, and Div. 3.

	Division 1	**Division 2**	**Division 3**
Published	**1940**	**1968**	**1997**
Structure of Code			
Organization	General, Construction Type and Material U, UG, UW, UF, UB, UCS, UNF, UCI, UCL, UCD, UHT, UL.	General, Material, Design, Fabrication and others AG, AM, AD, AF, AR, AI, AT, AS.	Similar to Division 2 KG, KM, KD, KF, KR, KE, KT, KS.
Design			
Pressure Limits	Normally up to 3000 psig.	No limits either way, usually 600+psig, no limit	Normally from 10,000 psig.
Design Factor	Design factor (DF) 3.5 on tensile (DF 4 was used earlier) and other yield and temperature considerations.	Design factor of 3 on tensile (lower factor under review) and other yield and temperature considerations.	Yield based with reduction factor for yield to tensile ratio less than 0.7.
Design Rules	Membrane—maximum stress generally elastic analysis. Very detailed design rules with quality (joint efficiency) factors. Little stress analysis required; pure membrane without consideration of discontinuities controlling stress concentration to a safety factor of 3.5 or higher.	Shell of revolution—max. shear stress generally elastic analysis. Membrane +bending. Fairly detailed design rules. In addition to the design rules, discontinuities, fatigue and other stress analysis considerations may be required unless exempted and guidance provided for in Appendix 4, 5, and 6.	Maximum shear stress elastic/plastic analyses and more. Some design rules provided; fatigue analysis required; fracture mechanics evaluation required unless proven leak-before-burst. Residual stresses become significant and may be positive factors (e.g., autofrettage).
Experimental Stress Analysis	Normally not required.	Introduced and may be made mandatory in future.	Experimental design verification but may be exempted.

Continued

Table 4-2-1 Continued

	Division 1	**Division 2**	**Division 3**
Published	**1940**	**1968**	**1997**
Material and Testing			
Impact Testing	Few restrictions on materials; impact required unless exempted; extensive exemptions under UG-20, UCS 66/67.	More restrictions on materials; impact required in general with similar rules as Division 1.	Even more restrictive than Division 2 with different requirements. Fracture toughness testing requirement for fracture mechanics evaluation crack tip opening displacement (CTOD) testing and establishment of KIc and/or JIc values.
NDE Requirements	NDE requirements may be exempted through increased design factor.	More stringent NDE requirements; extensive use of RT as well as UT, MT and PT.	Even more restrictive than Division 2; UT used for all butt welds, RT otherwise, extensive use of PT and MT.
Method of Construction			
Welding and fabrication	Different types with butt welds and others.	Extensive use/requirement of butt welds and full penetration welds includes nonpressure attachments.	Butt welds and other construction methods such as threaded, layered, wire-wound, interlocking strip wound etc.

Common Features: Jurisdictional requirements may be in addition to the Code requirements.
Mandatory Manufacturer's Quality Control System Implementation and Audit Requirements are imposed.
Code Stamp Authorization through ASME Accreditation and Authorization process.
Authorized Inspection Agency in accordance with QAI of ASME.
Authorized Inspector with Jurisdictional approval and certification may be additional requirements.
Manufacturer is held accountable for Code Stamp Application and full Code Compliance.
NDE Personnel qualification to SNT-TC-1A.
Note: This brief comparative table is presented for basic introduction and discussion and does not represent the opinion of the ASME or the ASME Boiler and Pressure Vessel Code Committees.
Readers are strongly advised to consult with the ASME Code Section VIII Divisions 1, 2, and 3 and jurisdictions requirements for more detail of the subject.

Table 4-2-2 Currently, the B 31 committee handles the following specifications.

	Number	Title
1	B 31.1	Power Piping
2	B 31.2	Fuel Gas Piping
3	B 31.3	Petroleum Refinery Piping
4	B 31.4	Liquid Petroleum Transportation Piping system
5	B 31.5	Refrigeration Piping
6	B 31.8	Gas Transportation and Distribution Piping system

ASME Code for pressure piping

ASME Code committees have developed codes for pressure piping, B31. Many sections of B31 committee include B31.1 for power piping and B31.3 for chemical piping. In addition, the B31 committee publishes a supplement on corrosion, B31G, entitled "Manual for Determining the Remaining Strength of Corroded Pipelines."

Some of the other pipeline-related design and construction specifications are given in Table 4-2-2.

ASME Section V

The ASME Code Section V is the reference Code that contains requirements for nondestructive examinations that are Code requirements and are referenced and required by other Codes; it has a total of 30 Articles, and some of them are not titled as listed in Table 4-2-3.

This section has two subsections.

Subsection A describes the methods of nondestructive examinations to be used if referenced by other Code Sections.

Subsection B lists the Standards covering nondestructive examination methods that have been accepted as standards.

The National Board

The National Board (NB) is an organization made up of law enforcement officials in the United States and Canada. They administer and enforce boiler and pressure vessel laws in their jurisdiction. The NB also standardized inspector qualifications and issue Commissions to Authorized Inspectors who successfully pass the examinations.

Authorized Inspection Agencies are the organizations that employ Authorized Inspectors. The Agency may be either the jurisdiction charged with the enforcement of the boiler or pressure vessel laws or an insurance company authorized to write boiler and pressure vessel insurance within a jurisdiction.

The National Board of Boiler and Pressure Vessel Inspectors is an organization comprised of Chief Inspectors, for the states, cities, and territories of the United States; provinces and territories of Canada; and Mexico. It is organized for the purpose of promoting greater safety to life and property by securing concerted action and maintaining uniformity in the construction, installation, inspection, repair, and alteration of pressure-retaining

Table 4-2-3 ASME Section V articles.

Article	Subject—Title
1	General Requirements
2	Radiographic Examination
3	Nil
4	Ultrasonic Examination Methods for in-service Inspection
5	Ultrasonic Examination Methods for Materials and Fabrication
6	Liquid Penetrant Examination
7	Magnetic Particle Examination
8	EDDY Current Examination of Tubular Products
9	Visual Examination
10	Leak Testing
11	Acoustic Emission Examination of Fiber-Reinforced Plastic Vessels
12	Acoustic Emission Examination of Metallic Vessels During Pressure Testing
13	Continuous Acoustic Emission Monitoring
14	NA
15	NA
16	NA
17	NA
18	NA
19	NA
20	NA
21	NA
22	Radiographic Standards
23	Ultrasonic Standards
24	Liquid Penetrant Standards
25	Magnetic Particle Standards
26	Eddy Current Standards
27	Leak Testing Standards
28	Visual Examination Standards
29	Acoustic Emission Standards
30	Terminology for Nondestructive Examinations Standard

items. This assures acceptance and interchangeability among jurisdictional authorities responsible for the administration and enforcement of various codes and standards.

The National Board Inspection Code (NBIC)

The purpose of the National Board Inspection Code (NBIC; http://www.nationalboard.org) is to maintain the integrity of pressure-retaining items after they have been placed in service by providing rules for inspection, repair, and alteration. This ensures that these objects may continue to be safely used.

The NBIC is intended to provide guidance to jurisdictional authorities, Inspectors, users, and organizations performing repairs and alterations. This encourages the uniform administration of rules to pressure-retaining items.

American Petroleum Institute

The American Petroleum Institute (API; http://www.api.org), located at 1220 L Street, Northwest, Washington, DC, 20005, is a trade association representing the entire petrochemical industry. The chemical process industry adopted the API standards for chemical process tanks and vessels. API began in 1919 evolving from the need to standardize engineering practices and specifications for drilling and production equipment. API has developed more than 500 standards related to the oil and gas industry. API requires certification of technical personnel involved in the inspection in the chemical and petrochemical industries.

The following is just a small sample of API specifications and codes that tries to reflect the variety of issues addressed by the institution.

API 42Y	Specification for Steel Plates, Quenched and Tempered for Offshore Structures
API 5L	Specification for Line Pipe
API RP 5L 1	Recommended Practice for Railroad Transportation of Line Pipe
API RP 5L W	Recommended Practice for Railroad Transportation of Line Pipe on Barges and Marine Vessels
API 1104	Welding of Pipeline and related facilities
API 6D	Specification for Pipeline Valves (Gate, Plug, Ball and Check Valves)
API 6A	Specification for Wellhead and Christmas-Tree Equipment
API RP 5L3	Recommended Practice for Conducting Drop-weight Tear Tests on Line Pipe
API 650	Welded Steel Tanks for Oil Storage

API also has several maintenance and inspection specifications that are common in use in petrochemical and oil and gas industry, some of which are described here.

API 653 (aboveground storage tanks)

The API 653 “Tank Inspection, Repair, Alteration, and Reconstruction” is the inspection code for welded or riveted, nonrefrigerated, atmospheric pressure, aboveground storage tanks for the petroleum and chemical process industries.

API 510 (pressure vessels)

The API 510 “Pressure Vessel Inspection Code: Maintenance Inspection, Rating, Repair, and Alteration” is the pressure vessel inspection code for the petroleum and chemical process industries.

API 570 (pressure piping)

The API 570 “Inspection, Repair, Alteration, and Rerating of In-Service Piping Systems” is the piping inspection code for the petroleum and chemical process industries.

API RP 579 (fitness for service)

The API RP 579 "Fitness for Service" is a recommended practice (RP). The purpose of the RP is to provide guidance as to the methods applicable to assessments that are specific to the type of flaw or damage encountered in refinery and chemical process plant equipment.

API RP 580 (risk-based inspection)

The API RP 580 "Risk-Based Inspection" is a RP. The purpose of the RP is to provide guidance as to the development of a risk-based inspection program with the methodology presented in a step-by-step manner for users in refinery and chemical process plants.

American Society for Testing Materials (ASTM)

ASTM specifications compliment most of the construction specifications; these specifications and codes address several material and testing procedures requirements and guidance. The specifications issued by American Society of Testing Material (www.astm.org) are organized on the basis of the type of material, and the letters prefixed to the specification number is indicative of the material type, for example letter A is for all ferrous materials; letter B is for all nonferrous materials; letter C is for Cementations, Ceramic, Concrete and Masonry; letter D is used to indicate specifications related miscellaneous material like to chemicals, polymers, paints, coatings, and their test methods etc.; similarly, letter E is used to denote specifications that address miscellaneous subjects, including subjects related to examination and testing of material. The following is a short list of some of these groups; the list is only to bring out the general explanation of what is described earlier.

ASTM A 6	Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheets Pilling.
ASTM A 20	Specification for General Requirements for Steel Plates for Pressure Vessels.
ASTM A 36	Specification for Carbon Structural Steel.
ASTM A 176	Specification for Stainless and Heat-Resisting Chromium Steel Plate, Sheet and Strip.
ASTM A 181	Specification for Carbon Steel Forgings for General Purpose Piping.
ASTM A 351	Standard Specification for Castings, Austenitic, Austenitic-ferritic (Duplex), for Pressure-Containing parts.
ASTM A 370	Standard Test Methods and Definitions for Mechanical Testing of Steel Products.
ASTM A265 - 12(2019)	Standard Specification for Nickel and Nickel-Base Alloy-Clad Steel Plate
A578/A578M	Specification for Straight-Beam Ultrasonic Examination of Rolled Steel Plates for Special Applications.
A751	Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products

Similarly, the nonferrous material list is exhaustive, and a few of them are listed here as an example.

ASTM B	Specification for Hand-Drawn Copper Wire.
ASTM B 80	Specification for Magnesium-Alloy Sand Castings.
ASTM B 159	Specification for Phosphor Bronze Wire.
ASTM B 418	Specification for Cast and Wrought Galvanic Zinc Anodes.
ASTM B 457	Test Method for Measurement of Impedance of Anodic Coating on Aluminum.
ASTM B 491	Specification for Aluminum and Aluminum-Alloy Extruded Round Tubes for General-Purpose Applications.
ASTM B 546	Specification for Electric-Fusion-Welded Ni-Cr-Co-Mo Alloy (UNSN06617), Ni-Fe-Cr-Si Alloy (UNS N08330 and UNS N08332), Ni-Cr-Fe-Al Alloy (UNS N06603), Ni-Cr-Fe Alloy (UNS N06025), and Ni-Cr-Fe-Si Alloy (UNS N06045) Pipes.
ASTM B547/ B547M-10	This specification for Aluminum and Aluminum-Alloy Formed and Arc-Welded Round Tube has since been withdrawn in 2019, but it is included because the material conforming to the specification is in the market and in use.

This specification covers aluminum and aluminum-alloy formed and arc-welded round tube in diameters 9–60 in. (230–1520 mm), made from formed sheet or plate, butt-welded by gas-tungsten or gas-metal arc-welding methods with or without the use of filler metal.

B127	Specification for Nickel-Copper Alloy (UNS N04400) Plate, Sheet, and Strip
B162	Specification for Nickel Plate, Sheet, and Strip
B168	Specification for Nickel-Chromium-Aluminum Alloys (UNS N06699), Nickel-Chromium-Iron Alloys (UNS N06600, N06601, N06603, N06690, N06693, N06025, N06045, and N06696), Nickel-Chromium-Cobalt-Molybdenum Alloy (UNS N06617), Nickel-Iron-Chromium-Tungsten Alloy (UNS N06674), Plate, Sheet, and Strip
B333	Specification for Nickel-Molybdenum Alloy Plate, Sheet, and Strip
B409	Specification for Nickel-Iron-Chromium Alloy Plate, Sheet, and Strip
B424	Specification for Ni-Fe-Cr-Mo-Cu Alloy (UNS N08825, UNS N08221, and UNS N06845) Plate, Sheet, and Strip
B443	Specification for Nickel-Chromium-Molybdenum-Columbium Alloy (UNS N06625) and Nickel-Chromium-Molybdenum-Silicon Alloy (UNS N06219) Plate, Sheet, and Strip.
B463	Specification for UNS N08020 Alloy Plate, Sheet, and Strip
B575	Specification for Low-Carbon Nickel-Chromium-Molybdenum, Low-Carbon Nickel-Chromium-Molybdenum-Copper, Low-Carbon Nickel-Chromium-Molybdenum-Tantalum, Low-Carbon Nickel-Chromium-Molybdenum-Tungsten, and Low-Carbon Nickel-Molybdenum-Chromium Alloy Plate, Sheet, and Strip
B582	Specification for Nickel-Chromium-Iron-Molybdenum-Copper Alloy Plate, Sheet, and Strip
B625	Specification for UNS N08925, UNS N08031, UNS N08034, UNS N08932, UNS N08926, UNS N08354, UNS N08830, and UNS R20033 Plate, Sheet, and Strip

Continued

Continued

B209	Specification for Aluminum and Aluminum-Alloy Sheet and Plate
B557	Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products
B660	Practices for Packaging/Packing of Aluminum and Magnesium Products
B666	Practice for Identification Marking of Aluminum and Magnesium Products
B881	Terminology Relating to Aluminum- and Magnesium-Alloy Products
B918	Practice for Heat Treatment of Wrought Aluminum Alloys
B947	Practice for Hot Rolling Mill Solution Heat Treatment for Aluminum Alloy Plate

The sample list of Cementations, Ceramic, Concrete, and Masonry Materials includes:

ASTM C 4	Specification for Clay Drain Pipe.
ASTM C 42	Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.
ASTM C 144	Specification for aggregate for Masonry Mortar.
ASTM C 150	Specification for Portland Cement.
ASTM C 155	Classification of Insulating Firebrick.
ASTM C 173	Test Method for Air Content of Freshly Mixed Concrete by Volumetric Method.

A sample list of Miscellaneous Materials is listed here.

ASTM D 20	Test Method for Distillation of Road Tars.
ASTM D 75	Practice for Sampling Aggregates.
ASTM D 98	Specification for Calcium Chloride.
ASTM D 143	Test Method for Small Clear Specimen of Timber.
ASTM D 185	Test Methods for Coarse Particles in Pigments, Pastes, and Paints.
ASTM D 388	Classification of Coals by Rank.
ASTM D 1621	Test Method for Compressive Properties of Rigid Cellular Plastics.
ASTM D 1640	Test Methods for Drying, Curing, or Film Formation of Organic Coating at Room Temperature.

A sample list of Miscellaneous Subjects is listed here.

ASTM E 4	Practices for Force Verification of Testing Machines
ASTM E 6	Terminology Relating to Methods of Mechanical Testing.
ASTM E 55	Practice for Sampling Wrought Nonferrous Metals and Alloys for Determination of Chemical Composition.
E29	Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.
E34	Test Methods for Chemical Analysis of Aluminum and Aluminum-Base Alloys

Continued

E227	Test Method for Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Point-to-Plane Technique
E527	Practice for Numbering Metals and Alloys in the Unified Numbering System (UNS)
E607	Test Method for Atomic Emission Spectrometric Analysis Aluminum Alloys by the Point to Plane Technique Nitrogen Atmosphere
E716	Practices for Sampling and Sample Preparation of Aluminum and Aluminum Alloys for Determination of Chemical Composition by Spectro-chemical Analysis
E1251	Test Method for Analysis of Aluminum and Aluminum Alloys by Spark Atomic Emission Spectrometry
ASTM E 83	Practice for Verification and Classification of Extensometers.
ASTM E 94	Standard Guide for Radiographic Examination.
ASTM E 73	Practice for Static Load Testing of Truss Assemblies.

A sample list of Materials for Specific Application is given here.

ASTM F 1	Specification for Nickel-Clad and Nickel-Plated Steel Strip for Electron Tubes.
ASTM F 22	Test Method for Hydrophobic Surface Films by the Water-Break Test.
ASTM F 78	Test Method for Calibration of Helium Leak Detectors by Use of Secondary Standards.

A sample list of Corrosion, Deterioration, and Degradation of Materials is given here.

ASTM G 1	Practice for Preparing, Cleaning, and Evaluating Corrosion test Specimen.
ASTM G 5	Reference Test Method for Making Potentiostatic and Potetiodynamic Anode Polarization Measurements.
ASTM G 6	Test Method for Abrasion Resistance of Pipeline Coatings.
ASTM G 11	Test Method for Effects of Outdoor Weathering on Pipeline Coatings.
ASTM G 36	Practice for Performing Stress-Corrosion Cracking Test in a Boiling Magnesium Chloride Solution.

These lists are just examples of the subjects addressed by each group; in fact, the actual list is exhaustive in each group. These specifications are from time to time amended, merged, removed, or changed, so the latest updated version must be referenced.

Det Norske Veritas (DNV)

Det Norske Veritas (DNV) describes itself as a provider of services for managing risk. It is one of the several classification organizations based in Oslo, Norway. Like Lloyd's Register and American Bureau of, the DNV was originally established to inspect, evaluate, and certify the technical condition of merchant vessels.

The maritime role of DNV has given this organization the edge over welding and fabrication of offshore structures and pipelines; as a result of this, DNV has developed several specifications relating to the design, welding, and testing of weldments. Although these specifications are titled differently, they have a significant effect on material and welding.

The following specifications are frequently used in offshore structure design, fabrication, and testing.

Offshore standard

- DNV-OS-C401 Fabrication and Testing of Offshore Structures.

  The standard intends to be used as technical reference document and guideline for design and procurement. This standard provides an international acceptance standard to the quality of all welding operations used in offshore fabrication. This includes the welding processes and welding qualification procedures, welders qualification, and testing thereof. The standard supports the other DNV specifications like DNV OSS-101 and DNV OSS-102 used for the installation of offshore structures.

  The specification also addresses the acceptable standard for coating and sacrificial anodes.
- DNV-OF F 101 Submarine Pipeline Systems

  This standard provides an international acceptance standard of safety for submarine pipeline systems by defining minimum requirements for design, materials, fabrication, and installation, testing commissioning, operations, repairs, requalification, and refurbishment. The standard is intended to serve as technical reference and guide to design and procurement.

Canadian Standards Association (CSA)

The Canadian Standards Association (CSA) is an organization that develops industrial standards spanning over 57 different industrial areas. This not-for-profit organization has representatives from industry, government, and consumer groups and publishes standards.

CSA is accredited by the standards Council of Canada, which is a crown corporation to develop and issue standards to promote standardization and efficiency in industrial production process in Canada.

The CSA standards are available in print and electronic form.

Starting as Canadian Engineering Standards Association (CESA) in early 1900s, the body was created as a result of Sir John Kennedy’s efforts to emphasize the need for such an organization. The initial approach was to address the needs of industries involved in production of aircraft parts, design and construction of bridges, construction of buildings, electrical work, etc. The first standards issued by CESA were for steel railway bridges, in 1920. CESA was renamed the Canadian Standards Association (CSA) in 1944. The certification mark was introduced in 1946.

Among the 57 different areas of specialization are climate change, business management, and safety and performance standards, including those for electrical and electronic equipment, industrial equipment, boilers and pressure vessels, compressed gas handling appliances, environmental protection, and construction materials.

Some of the CSA standards that relate to materials and welding are listed here.

CSA- B 51	Boiler, Pressure Vessel, and Pressure Piping code
CSA- B 53	Welded and Seamless Steel Pipe
CSA- W 59	Welded Steel Construction
CSA Z 183	Oil Pipeline Transportation Systems
CSA Z 184	Gas Pipeline Transportation Systems
CSA Z 662	Oil and Gas Pipeline Systems
CSA Z 245.1	Pipeline Systems and Materials
CSA Z 245. 11	Pipeline materials—Fittings,
CSA Z 245. 12	Pipeline materials—Flanges,
CSA Z 245. 15	Pipeline materials—Valves,
CSA Z 276	PLNG Production Storage and Handling
CAS W 48.1	Mild Steel Covered Arc-Welding Electrodes
CSA W 48.3	Low-Alloy Steel Arc-Welding Electrodes

Welding-related specifications from European norm and International Standards Organization

Without going much in detail of the history of how European Union had affected the common market and assimilation, which is termed as harmonization of various specification issued by different member countries into one Euro-Norm (EN), the objective being to set a common and equal ground for free flow of trade among the member countries. The concept is further extended to increase the common acceptable quality of welding works internationally through specifications issued by International Standard Organizations (ISO). Here too the EN specifications are harmonized with ISO specifications to present common acceptable grounds.

The list presents some of the specifications most commonly in use that affect welding and its quality management.

EN ISO 15607, specification and qualification of welding procedures for metallic materials—General rules

ISO 15607 was issued in 2003; it defines general rules for the specification and qualification of welding procedures for metallic materials. The specification also refers to several other standards as regards detailed rules for specific applications. ISO 15607 is applicable to manual, mechanized, and automatic welding.

EN ISO 15608, welding—Guidelines for a metallic materials grouping system

ISO 15608, issued in 2013, provides a uniform system for the grouping of materials for welding, heat-treatment, forming, and nondestructive testing. The specification covers the following groups of material.

- Steels
- Aluminum and its alloys
- Copper and its alloys
- Nickel and its alloys
- Titanium and its alloys
- Zirconium and its alloys
- Cast irons

EN ISO 15610, specification and qualification of welding procedures for metallic materials—Qualification based on tested welding consumables

ISO 15610, issued in 2003, gives the necessary information to explain the requirements referenced in ISO 15607 concerning the qualification of welding procedures based on tested consumables. In addition, it gives the range of qualification. The specification applies to arc and gas welding, but other fusion welding processes may be accepted if specified. It is limited to application to parent metals that produce acceptable microstructures and properties in the heat-affected zone that do not deteriorate significantly in service. This International Standard is not applicable where requirements for hardness or impact properties, preheating, controlled heat input, interpass temperature, and postweld heat-treatment are specified for the welded joint. The use of ISO 15610 may also be restricted by an application standard or a specification.

EN ISO 15611, specification and qualification of welding procedures for metallic materials—Qualification based on previous welding experience

ISO 15611, issued in 2003, gives the necessary information to explain the requirements referenced in ISO 15607 concerning the qualification of welding procedures based on previous welding experience. In addition, it gives the range of qualification and the validity.

The use of ISO 15611, like 15610, may be restricted by an application standard or a specification.

EN ISO 15612, specification and qualification of welding procedures for metallic materials—Qualification by adoption of a standard welding procedure

ISO 15612, issued in 2004, gives the necessary information and explains the requirements referenced in ISO 15607 about qualification by adoption of a standard welding procedure, and establishes the conditions, limits, and ranges of qualification necessary for the use of a standard welding procedure.

This International Standard gives the manufacturer the possibility of using welding procedures based on welding procedure tests performed by other organizations. The use of ISO 15612 can be restricted by an application standard or a specification.

EN ISO 15613, specification and qualification of welding procedures for metallic materials—Qualification based on preproduction welding test

ISO 15613, issued in 2004, specifies how a preliminary welding procedure specification is qualified based on preproduction welding tests. It is applicable to arc welding, gas welding, beam welding, resistance welding, stud welding, and friction welding of metallic materials. The use of this specification may be restricted by an application standard or specification.

EN ISO 15614, specification and qualification of welding procedures for metallic materials—Welding procedure test—Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

ISO 15614-1 was issued in 2004. This specification specifies how a preliminary welding procedure specification is qualified by welding procedure tests. It defines the conditions for the execution of welding procedure tests and the range of qualification for welding procedures for all practical welding operations within a range of variables. Additional tests may be required by application standards.

This ISO specification applies to the arc and gas welding of steels in all product forms and the arc welding of nickel and nickel alloys in all product forms. Arc and gas welding are covered by the following processes:

1. Manual metal arc welding (metal-arc welding with covered electrode)
2. Self-shielded tubular-cored arc welding
3. Submerged arc welding
4. Metal inert gas welding, MIG welding
5. Metal active gas welding, MAG welding
6. Tubular-cored metal arc welding with active gas shield
7. Tubular-cored metal arc welding with inert gas shield
8. Tungsten inert gas arc welding; TIG welding
9. Plasma arc welding
10. Oxy-acetylene welding

The principles of ISO 15614-1:2004 may be applied to other fusion welding processes.

EN ISO 9606 (five parts) welder approval testing

Part 1; Fusion welding of Steel Materials
Part 2; Fusion Welding of Aluminum and its Alloys
Part 3; Fusion Welding of Copper and Copper Alloys
Part 4; Fusion Welding Nickel and Nickel Alloys
Part 5; Fusion Welding Titanium and Titanium Alloys, Zirconium, and Zirconium alloys

EN 1418: Approval of Welding operators Fusion and Resistance Welding
BS EN 12732: Gas infrastructure: Welding steel pipework—Functional requirements
EN 13445 (original BS 5500, Harmonized as EN) Pressure Vessels
EN 12952 (original BS 1113, Harmonized as EN) Water Tube Boilers
EN 12953 (original BS 2790, Harmonized as EN) Shell Boilers
EN 13480 (original BS 806, BS 2971 but not included are piping specifications from BS 2640) Piping
EN 14242 Aluminum and Aluminum Alloys—Chemical Analysis—Inductively Coupled Plasma Optical Emission Spectral Analysis

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THIRD EDITION

APPLIED WELDING ENGINEERING

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A practical and in-depth guide to materials selection, welding techniques, and procedures, ***Applied Welding Engineering: Processes, Codes and Standards***, 3rd edition, provides expert advice for complying with international codes as well as working them into "day-to-day" design, construction, and inspection activities.

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Ramesh Singh, MS, IEng, MWeldI, is registered as Incorporated Engineer with The Engineering Council, UK, and a member of The Welding Institute, UK. He worked as an engineer for various operating and EPC organizations in the Middle East, Canada, and the United States. He is now consulting in the fields of welding, pipeline engineering, integrity and related materials, and corrosion topics.

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