•••POWER ENGINEERING

Fourth Class

Edition 3.5

Elements of Material Science and Welding Technology

Part A

Unit A-6

PanGlobal
Partner in Education

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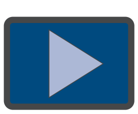
MEDIA 	Media icons show that some form of supporting medium is available. These media may include videos, animations, 2D and 3D models, multi-views of cutaways, simulations, and more. Media elements are available to registered textbook purchasers online via MyPower Study.
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UNIT A-6

Elements of Material Science and Welding Technology

Unit Introduction

Around one hundred years ago, boiler and pressure vessel explosions were common. Hundreds, if not thousands of serious accidents occurred annually; causing loss of life and significant property damage. Boiler operators were at risk every shift.

The boiler and pressure vessel industry today is far safer than it was 100 years ago. Power Engineering legislation and training made a huge impact on boiler and pressure vessel safety. However, the design and manufacture processes also advanced with the development of the various **ASME Boiler and Pressure Vessel** codes; which are now law in many North American jurisdictions.

Today, pressure vessels, pressure piping systems, boilers, and most other power plant equipment are designed and manufactured to provide reasonably long and safe service. To make equipment safe to operate, a manufacturer must:

a) Determine the service conditions, such as pressure and temperature.

b) Select the proper materials for the equipment service conditions.

c) Employ suitable production methods for the type of equipment and material being used. This includes welding and heat treatment.

d) Inspect the finished product to verify and document its quality.

This unit introduces the basics of boiler and pressure vessel construction. The first chapter shows how to identify, categorize, and select materials. These are based on properties that are the most useful such as strength, temperature resistance, and toughness. Also discussed is how engineering materials develop their properties.

In the next chapter, soldering, brazing, and welding methods are addressed. It also describes how these methods are used in the manufacture of pressure pipes, pressure vessels, and boilers.

The last chapter of this unit covers common weld defects and the non-destructive testing methods used by boiler and pressure vessel inspectors to find defects.

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Unit Rationale

Power Engineers are regularly exposed to the concepts in this unit. In fact, specifying materials, designs, welding procedures, and inspection techniques are all part of the job. Knowing design and material limitations helps power engineers operate equipment within safe limits. This knowledge also provides guidance for the proper maintenance and repair of the equipment for which Power Engineers are responsible.

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CHAPTER 1

Energy Plant Construction and Operation Materials

Learning Outcome

When you complete this chapter you should be able to:

Describe the mechanical properties of engineering materials used in engineering.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe the mechanical properties of materials.*
2. *Describe the various types of ferrous materials.*
3. *Describe the various types of non-ferrous materials.*

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Chapter Introduction

Material "properties" refer to a material's recognizable characteristics. These properties are how one material is distinguished from another. This helps to select the appropriate materials for specific applications.

Material properties can be classified as chemical or physical. Chemical properties mostly refer to a material's reactivity (such as corrosion resistance). Physical properties include:

a) Thermodynamic properties, such as boiling point, freezing point, and specific heat.

b) Electrical properties, such as conductivity and permeability.

c) Mechanical properties, such as **strength** and **ductility**.

A metal can be safely used under load only if its mechanical properties are known. The first part of this chapter looks at the mechanical properties of metals.

The second part of this chapter concerns ferrous metals. The word "**ferrous**" is derived from "ferrum," the Latin word for iron. Therefore, ferrous metals are those that contain iron (at least 50%, in the case of an **alloy**). Ferrous metals include pure iron and its alloys, such as **cast iron**, **steel**, and stainless steel.

Non-ferrous metals contain either no iron at all, or only small amounts. Some non-ferrous metals are copper, lead, aluminum, zinc, nickel, tin, and magnesium. These too are important to the Power Engineer, and are covered in the third part of this chapter.

Serviceability and safety are the ultimate criteria in choosing metals. Knowledge of metal properties, performance, and preservation are essential for ensuring boiler, pressure vessel, and pressure piping safety and long service life.

Objective 1

Describe the mechanical properties of materials.

Mechanical Properties

To measure and quantify a mechanical property, force must be applied to a material specimen (called a "**coupon**"). The coupon is a representative sample of the metal, machined to specific dimensions. Forces are applied to the coupon to twist, bend, break, flatten, pull apart, or shatter it.

Careful measurements are made of the applied forces and the dimensional changes the specimen undergoes during the application of the force. The test results are documented, so they may be compared to the behaviour of other metals under the same load conditions. Tests are repeated to validate the results. The results of the various tests reveal the material's mechanical properties, which are:

a) **Hardness**
b) **Brittleness**
c) Ductility
d) **Elasticity**
e) **Plasticity**
f) **Malleability**
g) Strength
h) **Toughness**

Hardness

Hardness is the ability to resist wear, abrasion, cutting, and indentation. A metal may be made hard only on the surface (a condition called "**case hardening**") or it may have the same hardness throughout. With regard to steel, hardness may be the single most important mechanical property. Knowing the hardness of a grade of steel, an engineer can infer its strength, ductility, toughness, and weldability.

Hardness tests typically check how well a material resists indentation. A hardened **steel** ball, cone, or pyramid is forced against the coupon to produce an indentation. For extremely hard materials, a diamond indenter would be used. Then, either the size or the depth of the indentation is measured. The hardness of the material is confirmed based on the measurement.

Another method of measuring hardness (the **Shore Hardness** method) does not make an indentation at all. A hard steel object called a "**tup**" is dropped from a measured height. Its rebound height after striking the metal is a measure of the hardness. This is used for materials such as plastics.

Hardness tests are named after the companies that developed the test methods and equipment. This chapter will discuss two common tests: the **Brinell Hardness Test** and the **Rockwell Hardness Test**.

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Brinell Tester

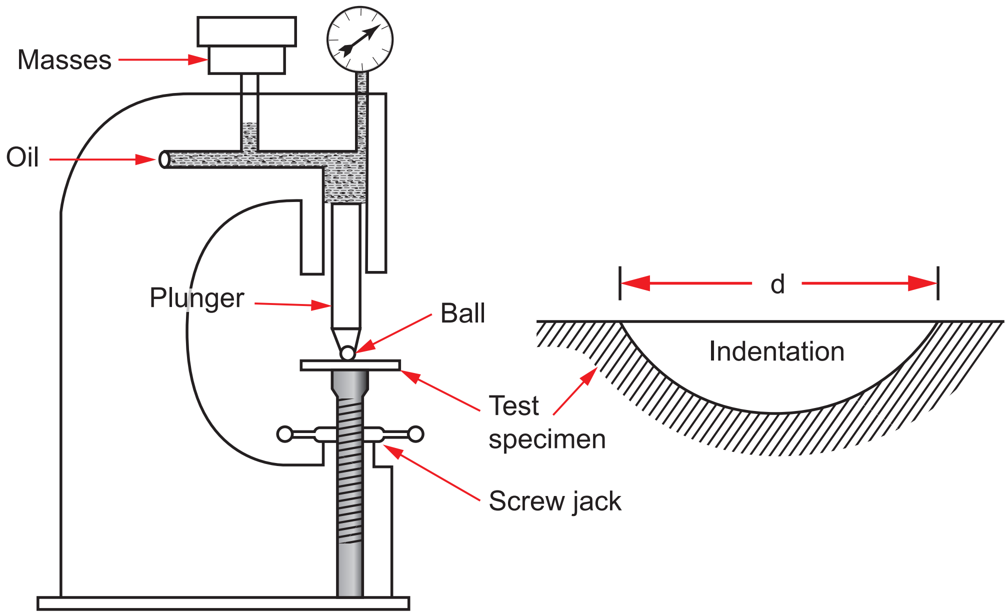
Figure 1 shows a Brinell hardness testing machine. The test coupon is placed on top of the screw jack and raised until it touches a 10 mm tungsten carbide ball (an extremely hard material). Then, a hydraulic pump forces oil above the plunger, pressing the ball into the test specimen. The pressure gauge gives an approximate indication of the load.

To assure no overload, the masses act as a pressure relief system. If the material is steel, the ball is forced into the test coupon by a standard 3000 kg load. For non-ferrous metals, the standard load is 500 kg. A low powered microscope is used to measure the diameter of the circular indentation made by the ball, the surface area of the mark is calculated, and the hardness determined as follows:

$$\textbf{Brinell Hardness Number (BHN)} = \frac{\text{Load (kg)}}{\text{Area of mark (mm}^2\text{)}}$$

Normally, the area of the mark is not calculated. Instead, the diameter of the depression is measured in mm. A chart is consulted from which the hardness number can be read directly.

Figure 1 – Brinell Hardness Tester



Rockwell Tester

The Rockwell tester uses a somewhat different principle. A 10 kg load is used to hold a 1.6 mm ball on the piece being tested. This small load flattens surface irregularities that may introduce errors into the test. Then, a 90 kg load is added to the 10 kg load, making an indentation. The 90 kg mass is removed and the 10 kg mass left on.

The dial of the instrument measures the depth of the mark to within 0.002 mm. It converts the depth to a hardness reading, which is read from a dial indicator. For hard materials, a diamond cone is used and the total load is 150 kg. To avoid confusion, readings made with the ball are called **Rockwell B** readings, while those with the cone are called **Rockwell C** readings.

Brittleness

A **brittle** material will break (usually with a snap), rather than remain deformed. Brittleness does not imply that a material is weak; many strong materials are also brittle (such as **white cast iron**). Brittleness refers, then, only to a material's failure mode. Because brittle materials break without any intermediate stage of bending, they provide little warning that they are about to fail. This is why boiler and pressure vessel metal must never be brittle. Another example of a brittle material is cast iron.

Ductility

Ductility is the property of a material that enables it to be drawn out to a considerable extent before breaking. Ductility may be considered to be the ability of a material to be permanently deformed under a tensile load without breaking. Mild steel and pure irons are **ductile** materials. Ductile metal may be cold-drawn into wires, as in annealed copper.

Elasticity

Elasticity refers to the ability of a material to return to its original shape after a deforming force has been removed. It is one of the most important properties, from the engineering point of view, because it helps determine the behavior of the material under a load. Materials that are tough and ductile, such as **wrought iron**, possess a certain amount of elasticity. Hard and brittle materials, such as cast iron, have very little elasticity.

Plasticity

A material scientist would define a material that exhibits plasticity, or is **plastic**, if it is very soft and easily deformed. Plastic materials have very little elasticity; that is, they do not return to their original shape after the deforming force has been removed. Plasticity is the opposite of brittleness.

Side Track

Do not confuse the material scientist's definition of "plastic" with the definition we commonly use (synthetic material for manufacturing a wide range of consumer goods).

Examples of materials with high plasticity include wax, lead, and babbitt (a non-ferrous metal alloy used for bearings).

Malleability

Malleability is that property which allows a material to be hammered or rolled into other sizes and shapes. In other words, malleability is the ability of a material to be permanently deformed under a compressive load, without breaking. Many ductile materials are also malleable, such as copper. The malleability of most materials increases when the material is heated, such as when iron, or steel are heated before forging.

Strength

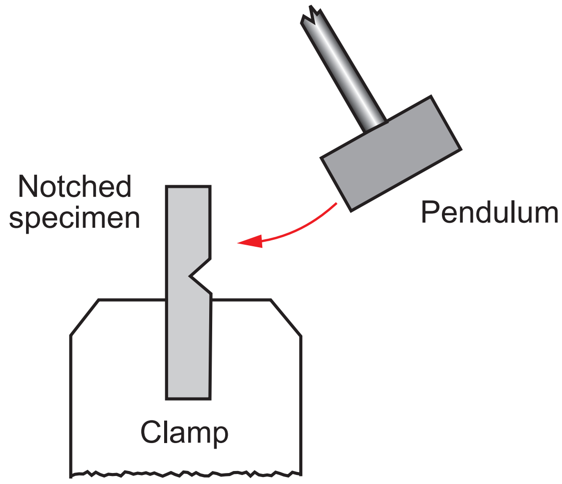
Strength is the property that allows a material to resist deformation under load. A weak material lacks strength and fails under a small load, whereas a strong material requires a large load to cause it to fail. Three important strengths are Yield Strength, Ultimate Strength, and Impact Strength (or "toughness"). Yield strength is the load a material can withstand before undergoing plastic deformation. Ultimate strength is the maximum load a material can withstand before breaking. Impact strength is described next.

Toughness

Toughness is also referred to as "impact strength". This property informs engineers whether a material will break under a sudden impact or hard blow. This property, like malleability, is temperature dependent. For example, as steel becomes colder, it loses its toughness.

Two commonly used toughness tests are the **Izod** and the **Charpy** (pronounced "sharpy"). In the **Izod test** (Fig. 2), one end of a material specimen is held in a vice; the free end is struck with a hammer. The energy required to break the specimen is measured and indicates the toughness of the material.

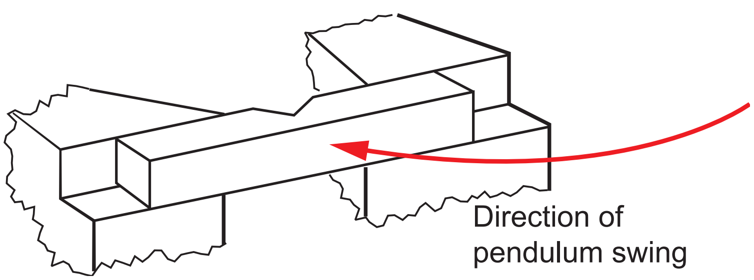
Figure 2 – Izod Impact Test



The Charpy test is similar, except that the specimen to be tested is simply supported at each end, and struck in the centre with the hammer. In the Charpy Test (Fig. 3), a round or square specimen is machined into specific dimensions, notched, and then broken by a blow from a pendulum.

The amount of energy used in breaking the specimen is determined by recording the initial pendulum height and the height to which the pendulum rises after the break. The difference in these heights is used to calculate the energy absorbed by the specimen, in Joules.

Figure 3 – Charpy Impact Test



Objective 2

Describe the various types of ferrous materials.

Types of Ferrous Materials

Design engineers specify many ferrous metals in the construction of equipment Power Engineers operate and maintain equipment, including cast iron and steel. However, cast iron and steel cannot be made without first making **pig iron** from **iron ore**. Wrought iron, which is nearly pure iron, is of historical significance only. Boilers and pressure vessels have not been made of this material for over 100 years.

Pig iron, cast iron, wrought iron, and steel begin as iron ore. They develop their unique properties during the refining process.

Pig Iron

Pig iron is the first material produced by the iron ore refining process. Iron ore, coke (a fuel source), and limestone are added in layers to a blast furnace, where the mixture is heated to around 2000°C. The limestone melts at this high temperature, and combines with impurities to form a slag. This slag, which floats on top of the molten pig iron, is drawn off and discarded. The molten pig iron is "tapped" into ladles or cast into molds.

Pig iron, by itself, is of little or no use. Because it contains greater than 4% carbon, it is hard, brittle, and almost impossible to machine. It cannot be worked whether hot or cold. To make the pig iron useful, it must be refined further into cast iron or steel.

Cast Iron

Cast iron is an alloy of iron and carbon. Despite its name, cast iron is not pure iron. The term "cast iron" is vague, because there are several types of materials with widely different mechanical properties that are all referred to as "cast iron":

- White cast iron
- **Grey cast iron**
- **Malleable cast iron**
- **Ductile iron**

All cast irons are produced by melting pig iron together with some scrap iron in a **cupola furnace** (a small blast furnace). The resulting molten iron contains 2% - 4% dissolved carbon. As the molten cast iron cools, the carbon can become chemically combined with the iron (a compound called iron carbide), or it may precipitate out of the cast iron as flakes or nodules (referred to as "mechanically held" carbon).

If most of the carbon is chemically combined with the iron, the material is called white cast iron. White cast iron is made by cooling the molten cast iron rapidly in a mold, which prevents the carbon from precipitating out of solution. Thus, the carbon remains combined with the iron. White cast iron is very hard and brittle. It is used for machinery parts that are subjected to excessive wear, such as crusher jaws and grinding mill balls and liners.

If molten cast iron is allowed to cool slowly, much of the carbon precipitates and becomes mechanically held in the iron. If most of the carbon precipitates as graphite flakes, the material is known as grey cast iron. Grey cast iron is softer than white cast iron and is easily machined. It has good compressive strength and is widely used for machinery bases and internal combustion engine components.

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Another product made from the same molten cast iron is malleable cast iron. This material is produced by **annealing** white cast iron (heating and cooling it at a controlled rate). The resulting material has increased toughness and ductility. Malleable iron is used for farm implements, automobile parts, pipe fittings, and tools.

Wrought Iron

A process known as "puddling" produces wrought iron. Pig iron is melted in a furnace and, as it melts, the carbon and other impurities oxidize and leave the iron. As the impurities pass off, the iron forms a plastic mass, which is formed into a ball by the manipulation of a puddling bar. The ball is then removed from the furnace and squeezed and rolled to remove most of the slag. The result is wrought iron.

The important properties of wrought iron are its ductility and resistance to corrosion. It was formerly used extensively for boiler tubes, piping, and bolts but has been entirely replaced by steel.

Steel

Steels are also alloys of iron and carbon, but contain less than 2% carbon. If the carbon content is greater than 2%, the resulting alloy is cast iron. Steels may be divided further into **plain carbon steel** and **alloy steel**. Plain carbon steels are alloys of iron and carbon only. Alloy steels will also contain considerable amounts of other metals, such as chromium, nickel, and molybdenum.

The majority of steel manufactured in the world is produced using the **basic oxygen furnace**, or "**BOF**". The furnace is called "basic" for two reasons:

1. The furnace lining is made of high pH refractory (calcium oxide and magnesium oxide).
2. The fluxing agent for removal of impurities is also basic (limestone).

A modern BOF will take a charge of iron of up to 350 tonnes of pig iron and scrap, and convert it into steel in less than 40 minutes.

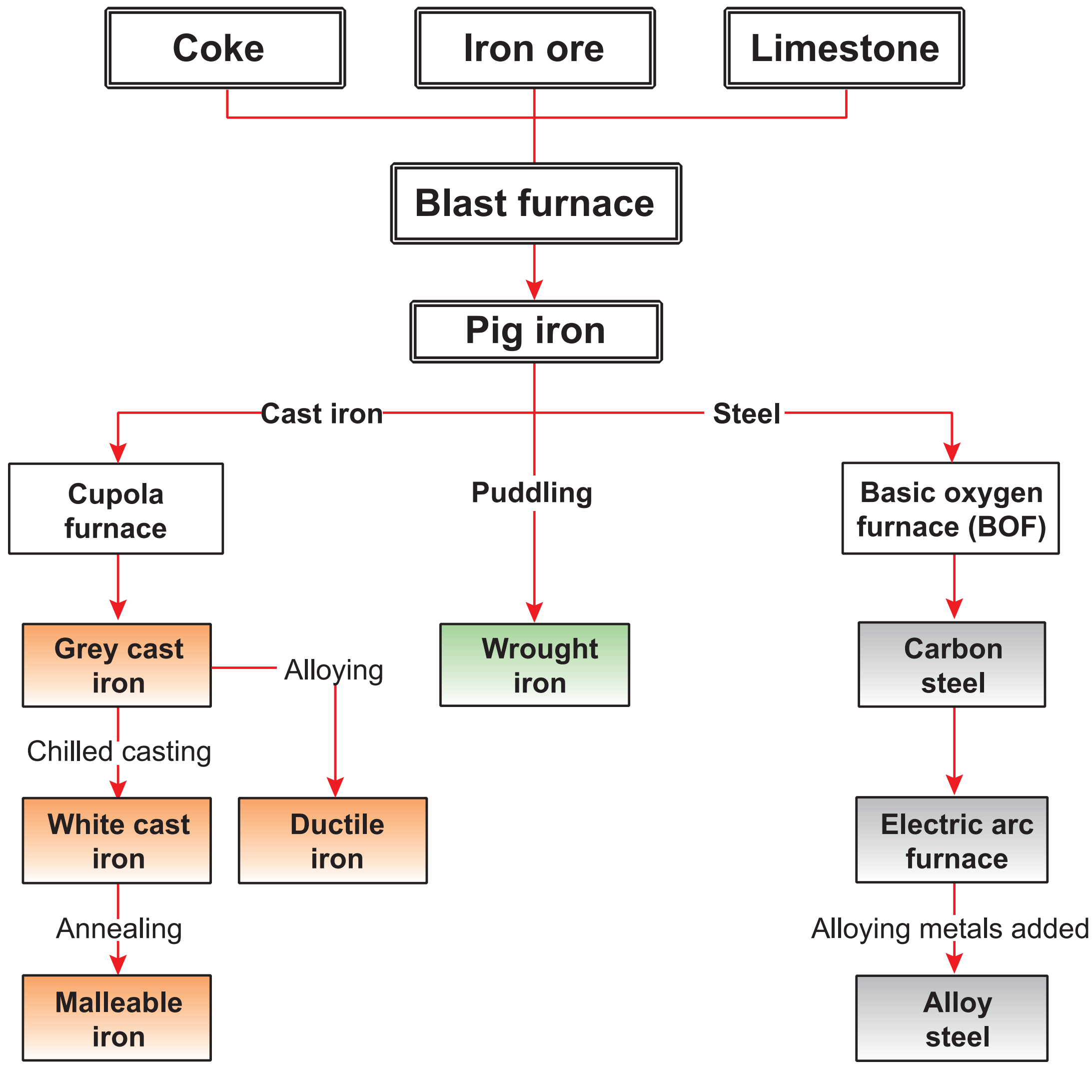
The BOF is fed with scrap iron and steel, molten pig iron from the blast furnace, and limestone. Oxygen is blown into the furnace through a water-cooled oxygen lance, which oxidizes the carbon and other unwanted elements in the hot metal. As the charge in the furnace is heated and melted, the carbon content is reduced to the proper point, producing carbon steel. If alloy steel is desired, the required alloying materials are added to the molten carbon steel.

The excess carbon in the pig iron is burned to carbon monoxide in the BOF. This "**offgas**" passes from the furnace to a cleaning plant. After cleaning, it can be re-used as a fuel gas. The rest of the elements in the metal are converted to acidic oxides. They combine with the limestone and other fluxes that are added during the initial furnace charging, mainly to neutralize the acidic oxides and prevent excessive wear of the furnace lining. As well, limestone combines with sulfur impurities in the molten steel. These chemical processes produce a slag that floats on the surface of the metal.

When it is at the correct temperature and chemical composition, the steel is tapped from the furnace. The BOF is tilted, causing the molten steel to run out of a tap-hole into a ladle. Once the steel has been removed, the furnace is tilted in the opposite direction, and the slag remaining inside runs into another ladle. The solidified slag can be used in the production of cement and as an aggregate in road building.

Figure 4 is a chart that summarizes the various ferrous metals covered in the text, and the process by which they are made, starting with the raw materials.

Figure 4 – Ferrous Metals Making Process



Special high alloy steels are produced in electric furnaces, where the heat is furnished by electric arcs.

Plain Carbon Steels

Carbon steels are grouped according to their carbon content.

Low Carbon Steels

Low carbon steels have carbon content between 0.05% and 0.3%, and are commonly referred to as mild steel. These steels are easily formed and welded. The boiler plate is made from mild steel because it is easily welded, without using special weld procedures.

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Medium Carbon Steels

These steels have a carbon content varying between 0.3% and 0.45%. They are strong and hard, but not easily welded. Whenever the carbon content exceeds 0.35%, the steel becomes increasingly difficult to weld, due to a greater tendency toward brittleness.

High and Very High Carbon Steels

The carbon content for high and very high carbon steels ranges from 0.45% to 0.75% and from 0.75% to 1.5%, respectively. They are very strong and hard. Hardness and strength increase with an increased carbon content. Impurities, such as phosphorus or sulfur, will lower the ductility, malleability, and weldability of steel. High and very high carbon steels respond well to heat treatments. High carbon steel may be annealed, which softens it to allow machining. After machining, the original hardness can be restored by further heat treatment.

Alloy Steels

Alloy steels are carbon steels to which certain elements have been added. Each of these elements improves the mechanical or chemical properties to the steel. Some of the alloying elements combine with the carbon to form compounds; other elements do not form compounds, but remain in solid solution. A solid solution is one where alloying elements do not combine with other elements, but are held suspended in the material's crystal structure.

The main advantages of alloy steels are:

a) Ability to respond to heat treatment.
b) Improved corrosion resistance.
c) Improved properties at high and low temperatures.
d) Combination of high strength with good ductility.

Most alloy steels may be welded, provided the carbon content is within welding range. Generally, these steels require heating before, during, and after welding in order to avoid residual stresses.

An example of an alloy steel is chrome molybdenum steel used for high temperature steam piping. This material is suitable for severe service because of its high creep strength, and resistance to oxidation, corrosion, and erosion at high temperatures (to above 500°C). Creep is slow, permanent stretching of a material under stress at high temperatures.

The following are some of the most important elements added to steel to produce alloy steel and their effect on the properties of the steel.

Nickel

Nickel is a tough, silvery metallic element of about the same density as copper. It has excellent resistance to corrosion and oxidation even at high temperatures. It improves toughness and prevents brittleness at low temperatures.

Nickel steels are especially suitable for the case hardening process for such applications as roller bearings and gears. These steels provide strong, tough cases resistant to wear and fatigue.

Chromium

Chromium resists oxidation caused by hot gases, maintains high strength at elevated temperatures, and increases hardness and abrasion resistance. When chromium is present in amounts in excess of 4.0%, corrosion resistance is greatly promoted. Steel is called stainless steel if it contains at least 12% chromium.

Molybdenum

Molybdenum increases the hardness and endurance limits of steel, and increases creep strength. It also increases steel's corrosion resistance.

Vanadium

Vanadium produces a fine grain structure during heat treatment, promotes hardening ability, and increases ductility.

Copper

Copper readily combines with many other elements, and improves the atmospheric corrosion resistance qualities of the steel.

Lead

Lead improves machinability.

Manganese

Manganese increases strength and hardness, promotes high impact strength, and offers excellent resistance to wear by abrasion.

Tungsten

Tungsten produces a fine grain structure. The alloy retains hardness and strength at high temperatures.

Objective 3

Describe the various types of non-ferrous materials.

Non-Ferrous Metals

Design engineers also specify many non-ferrous metals for powerhouse equipment. Non-ferrous metals may not be as strong or hard as ferrous metals, but have other important properties which make them more suitable for a variety of applications.

The following are types of non-ferrous materials that are used in power plants.

Copper

Copper is obtained from copper ore, which is smelted and then further refined by electrolysis. It is then made into castings, wire, bars, sheets, plates, and tubes. These properties make copper a desirable engineering material:

- high electrical conductivity
- high heat conductivity
- high corrosion resistance
- high ductility
- toughness

In a power plant, copper is used primarily for electrical equipment and piping. Alloys of copper are used for heat exchanger tubes, valves, and fittings.

Copper Alloys

If molten copper is mixed with other metals, the resulting alloy has superior properties to pure copper. Copper alloys are stronger, easier to machine, and have better corrosion resistance than pure copper. The most commonly used copper alloys are various **brasses** and **bronzes**, which find use as condenser tubes, piping, valves, fittings and bearing shells.

Brass

Brasses are primarily mixtures of copper and zinc (up to 40%). Frequently, small amounts of other metals such as lead, tin, nickel, aluminum, and manganese are also included in the alloy.

Bronze

Bronze is an alloy of copper and tin, but may also contain zinc (which ensures non-porous castings and leads to improved machining qualities). Additions of up to 1% phosphorus produce bearing bronzes, which are hard but not abrasive. Bronze has a resistance to corrosion approximately equal to that of copper.

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Aluminum

Aluminum is produced by electrolysis from bauxite ore. One of its most important properties is its low density; it is only one third as heavy as iron or steel. Aluminum is:

- very malleable and ductile
- a good conductor of electricity
- an excellent conductor of heat
- highly resistant to corrosion

Unfortunately, in its pure form, aluminum has a low tensile strength.

Aluminum is usually alloyed with other materials such as copper, silicon, manganese, zinc, nickel, magnesium, and chromium in order to improve its properties. For example, an aluminum alloy may contain 4% copper and 0.5% each of manganese and magnesium. Aluminum alloys are used for internal combustion engine parts, aircraft parts, tubing, and water jackets.

White Metal (Babbitt)

White metal (also known as babbitt) is the name given to alloys made primarily of lead and tin, which in some cases have small amounts of other elements added such as antimony, copper, or arsenic.

Babbitts are chiefly used for bearing materials because they are easily melted and cast in the bearing shell. They have sufficient strength and ductility so they do not crack or squeeze out under heavy loads. In addition, they are malleable enough to wear sufficiently to conform to the shape of the shaft, and they have good thermal conductivity to carry heat away from the bearing surface.

Different applications use babbitts of different composition; the material used for a high speed industrial turbine bearing would be different from that used in an internal combustion engine. Babbitt material must be able to absorb and retain a lubricant film on the surface, and must be soft enough that foreign matter may embed in it, preventing scoring of the shaft.

Tin based babbitt, typically composed of 85% tin (Sn), 7% antimony (Sb), 7% copper (Cu), and 0.35% (max) lead (Pb), is often used for turbine bearings. Tin based babbitt is better for higher speeds (730 m/min or 2400 ft/min at the surface of the shaft) and higher loads (900 kg or 200 lb) than lead-based babbitt.

Lead-based babbitt is typically composed of 5% tin 14.5% antimony, 0.3-0.6% arsenic (As) and approximately 80% lead. The lead-based babbitt is acceptable for lower speeds (300 m/min or 1000 ft/min at the surface of the shaft) and lower loads (225 kg or 500 lb). The main advantage of lead-based babbitt is its cost; lead is relatively inexpensive compared to tin.

Chapter Summary

Safety and serviceability are the ultimate criteria in choosing metals. Design engineers carefully choose the most suitable metals for various applications, based on expected service conditions:

- Temperature
- Load
- Corrosiveness
- Life cycle

The design engineer's decision considers both physical and chemical properties of the material, and how it will respond to its service conditions.

Metallurgists study and test the properties of metals. They continuously improve metals by developing new alloys with superior properties, and maintain catalogues of metals to assist in the engineers' selection.

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CHAPTER 2

Introduction to Welding

Learning Outcome

When you complete this chapter you should be able to:

Describe welding processes relevant to the plant and Power Engineering.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe non-fusion welding process, equipment used, and methods.*
2. *Describe forge and oxy-fuel fusion welding processes and cutting processes.*
3. *Describe metal arc welding processes.*
4. *Describe heat treatment of welds.*
5. *Describe the types of weld joints used in pressure vessel construction.*
6. *Describe the additional construction components required for pressure vessels to ensure structural integrity and "access."*

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Chapter Introduction

To the inexperienced, welding seems to be simple: melt some metal pieces, join them together, and allow the molten metal to cool and solidify. The experienced, though, know how difficult it is to make a weld that is as strong, ductile, and durable as the metal pieces being joined.

Welding, if done improperly, can actually reduce the strength of the **parent metal**. Poor welding technique can introduce gas pockets or solid impurities into the weld metal. The heat from welding and flame cutting can make weld metal brittle, and susceptible to cracking and fracture. Improper weld methods may physically distort a structure, making it useless.

Even a well-executed weld may weaken a structure if the weld joint is not designed using sound engineering practice. Ultimately, a weld joint that is defective will not be strong enough for the service conditions it will encounter. A defective weld is a dangerous weld.

Therefore the **American Society of Mechanical Engineers** (**ASME**) has published strict rules for creating safe, strong, and durable weld joints (ASME IX). Every province in Canada has laws stipulating that boilers, pressure vessels, and pressure piping be made in accordance with **ASME Code Section IX**. As well, similar rules have been developed by the Canadian Welding Bureau for structural welding (bridges, buildings, etc.).

This chapter will introduce welding, with respect to **ASME IX**. As progression is made through Power Engineering materials, this code will become increasingly familiar.

Welding Defined

ASME IX defines welding as:

> *"A localized coalescence of metals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler material."*

So, welding involves:

a) Heating metal and causing the metal to coalesce (join together)

b) Optionally applying pressure to the weld joint during welding

c) Optionally adding **filler metal** to the weld joint

The **base metal** (the pieces being joined together) is also called the parent metal. Material that is added to the weld joint during welding is called filler metal.

There are two main categories of welding: **non-fusion welding** and **fusion welding**.

Non-fusion welding does not involve melting the parent metal; only the filler metal melts. This may be difficult to imagine, but consider **soldering** and **brazing**: both are forms of non-fusion welding. The filler metal in a non-fusion process melts at a much lower temperature than the parent metal, and joins the parent metal pieces with a very strong adhesive bond.

Fusion welding, on the other hand, is "the melting together of filler metal and base metal or of base metal only, to produce a weld" (**ASME IX**). The molten parent and filler metal mixes together, and solidifies into a very strong, single metal piece.

Objective 1

Describe non-fusion welding process, equipment used, and methods.

Non-Fusion Welding

Non-fusion welding is commonly known by the terms brazing and soldering. Brazing and soldering are similar in that:

a) Both are adhesive processes.

b) Both use capillary action to draw the filler metal into the weld joint, where it adheres to the surfaces being joined.

c) Both use filler metal which is different from the parent metal.

However, brazing and soldering differ in that:

a) Soldering is weaker than brazing.

b) Soldering is done at lower temperatures than brazing.

c) Soldering cannot be used to build-up the thickness of the weldment, whereas brazing can.

d) Soldering is not permitted by ASME for boiler, pressure vessel, or pressure piping construction. Brazing, however, may be used for boiler construction.

Soldering

Soldering (or "soft soldering") is performed at temperatures below 450 degrees Celsius. The filler metal is usually made of varying proportions of tin and lead, with minor additions of alloying metals such as antimony, silver, and copper.

Though not used for boiler construction, soldering is commonly used for connecting copper fittings and pipe. Water supply piping systems and drainage, waste and vent (DWV) piping systems are usually soldered.

Brazing

Brazing is performed at temperatures above 450 degrees Celsius, but below the melting point of the parent metal. Brazing rods are made of bronze, which is an alloy of copper and tin, or brass, which is an alloy of copper and zinc. Typically, these rods melt around 900 to 1000 degrees Celsius.

Because brazing metal is stronger, and more heat resistant, **ASME IV** (the low-pressure heating boiler code) allows boilers to be constructed of brazed-together copper tubing. These copper heating boilers are very common because copper is an excellent heat conductor.

Silver Brazing

Silver brazing (or "hard soldering") is a form of brazing frequently used for assembling copper compressed air piping systems and refrigerant tubing. Silver brazing is also used for repairing copper heat exchanger tubing. The filler metal is strong at high temperature, adheres well to copper, and can be used to build-up the weld deposit thickness if necessary.

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Non-Fusion Welding Methods

To braze or solder, the worker must first:

1. Ensure the parts fit properly.
2. Clean the grease, dirt, paint, and oxidation from the parts being joined.
3. Apply **flux** to the surfaces being joined. Flux is a material that:
    a) Prevents oxidation of the metal surfaces while they are being heated.
    b) Keeps the joint surfaces clean.
    c) Encourages the smooth flow of filler metal into the joint.

Next, heat is applied to the joint, usually using a propane or **oxyacetylene** hand torch. Propane and **acetylene** are fuels that produce great heat when burned. Acetylene produces higher temperatures and more heat than propane, so it is used for brazing or for very large soldered joints. If more heat is required, **MPS gas** (**Methylacetylene-propadiene**) may be used instead of propane.

When the proper temperature is reached, the filler metal is applied. For brazing, a dull red glow indicates the parent metal is hot enough. The filler metal must be applied to all the surfaces being joined, and in adequate quantity to penetrate the entire joint.

After the parts cool, the remaining flux must be cleaned from the surfaces. Flux may be acidic; residual flux may corrode the parent material and weaken it over time.

Equipment for Non-Fusion Welding

The equipment for brazing and soldering must provide the correct amount of heat for the job being done.

Soldering is done at a lower temperature than brazing, thus soldering requires less heat. A simple hand torch, combined with a propane bottle, is adequate for soldering copper tube up to one inch in diameter. The torch itself is a small premix burner with an orifice that meters the flow of propane to the burner tip. Air and propane mix in the mixing chamber of the burner before igniting at the burner tip.

For soldering copper pipe in sizes up to two-inch, MPS gas can be used instead of propane. MPS gas burns at a higher temperature than propane, and has a greater heating value. As well, MPS does not need to burn with oxygen in order to achieve a high flame temperature. For soldering pipe sizes greater than two inches in diameter, oxyacetylene torches can be used.

Oxyacetylene outfits are used for brazing, in order to provide the necessary high flame temperatures and heat input. MPS gas can also be used for brazing smaller jobs. Oxyacetylene outfits are discussed later, under oxy-fuel welding.

Objective 2

Describe forge and oxy-fuel fusion welding processes and cutting processes.

Forge Welding

Historically, welding was performed in a blacksmith shop. The blacksmith used a forge to join metal pieces. The forge heated the parent metal pieces to between 50 and 90 percent of their melting temperature, so that the metal would become soft. Then, the blacksmith would overlap the parent metal pieces, and apply force using a hammer. The combination of force and heat would cause the metal pieces to weakly fuse together.

Forge welding is not used for welding today, except by enthusiasts and artisans interested in historical methods of joining metal. The weld joints formed by forge welding are too weak to serve any modern industrial purpose.

Fusion Welding

Fusion welding produces the strongest possible weld joints. In fact, a fusion-welded joint may be stronger than the parent material itself! This is because with fusion welding, the parent metal melts and mixes together. Upon cooling, the weld metal solidifies into a single continuous piece of metal.

Fusion Welding Processes

Fusion welding is performed in a variety of ways, called weld processes. The ASME identifies many acceptable processes, and gives each an abbreviation. Several of these deserve further study. They are commonplace and very important in the manufacturing of boilers, pressure vessels, and pressure piping.

Figure 1 – Welding Processes – An Overview

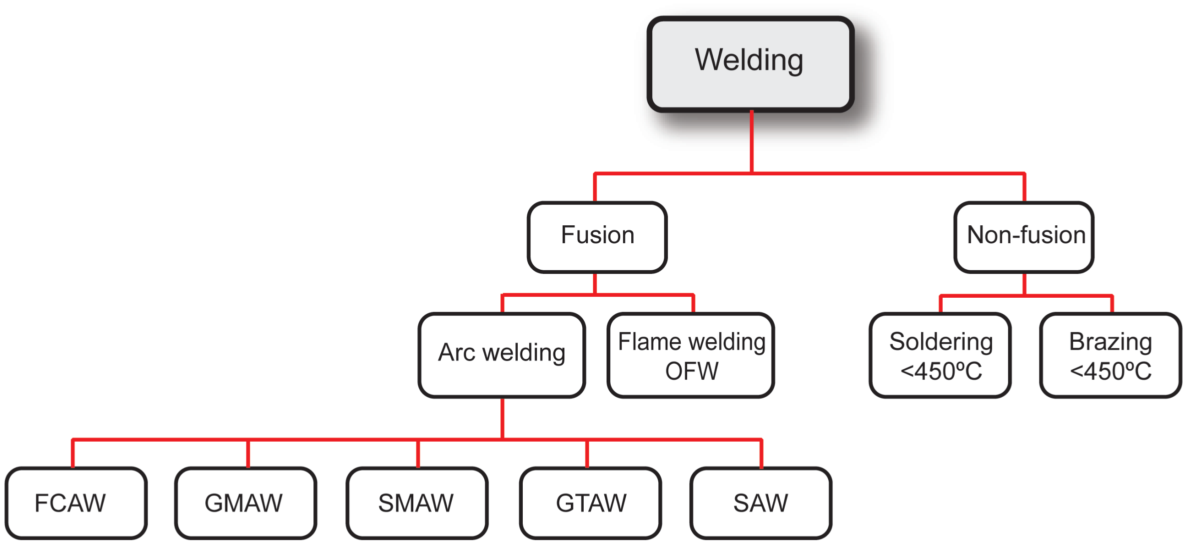

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Table 1 – A Partial List of ASME IX Weld Processes

ASME Designation	Proper Name	Common Name(s)	Weld Progression
OFW	Oxy-fuel welding	Oxyacetylene, flame welding	Manual
SMAW	Shielded metal arc welding	Arc welding, stick welding	Manual
GMAW	Gas metal arc welding	MIG welding	Semi-automatic
GTAW	Gas tungsten arc welding	TIG welding, Heliarc welding	Manual
SAW	Submerged arc welding	none	Fully automatic

Of these processes, only one uses a flame as a heat source (OFW). The others use the heat generated from an electric arc. **OFW**, **SMAW**, **GMAW**, **GTAW**, and **SAW** will be discussed in this text.

Oxy-Fuel Welding (OFW)

The ASME does not limit the fuel used in OFW to acetylene. Propane and other gases are also used. However, acetylene is most commonly used because it yields the hottest flame. Therefore, keep in mind that the term "OFW" covers a broad range of oxy-fuel processes, and that oxyacetylene – though common - is only one of many OFW processes.

Unlike brazing or forge welding, OFW heats the parent metal to above the melting temperature of the parent metal. OFW can be performed with or without filler metal. If filler metal is added, it is the same composition as the parent metal.

OFW is a **fully manual process**. This means that the rate at which the weld progresses (millimetres per minute), and the rate of filler metal addition, are both controlled by the person performing the weld. Therefore, it takes considerable skill and co-ordination to produce a strong, pressure-vessel quality weld using OFW.

In an oxyacetylene outfit, the acetylene burns at the tip of the torch pre-mixed with pressurized, pure oxygen. This causes the fuel to burn at a higher temperature, and at a faster rate. The faster a fuel burns, the more heat is developed per unit time. With only the oxygen available in the atmosphere, acetylene burns at about 2500 degrees Celsius. With a pure pressurized oxygen supply, acetylene burns at around 3300 degrees Celsius, which is hot enough to melt steel.

OFW, though still permitted by **ASME IX**, has fallen out of favour with boiler, pressure vessel, and pressure piping manufacturers. OFW is slower than the **arc welding** processes, involves the use of both hands (one for the torch and one for the filler rod), and it is harder to control the quality of the weld. Despite this, OFW is still commonly used for non-structural maintenance and repair. The advantage of OFW is that the equipment is portable, and does not rely on an outside power source to be used.

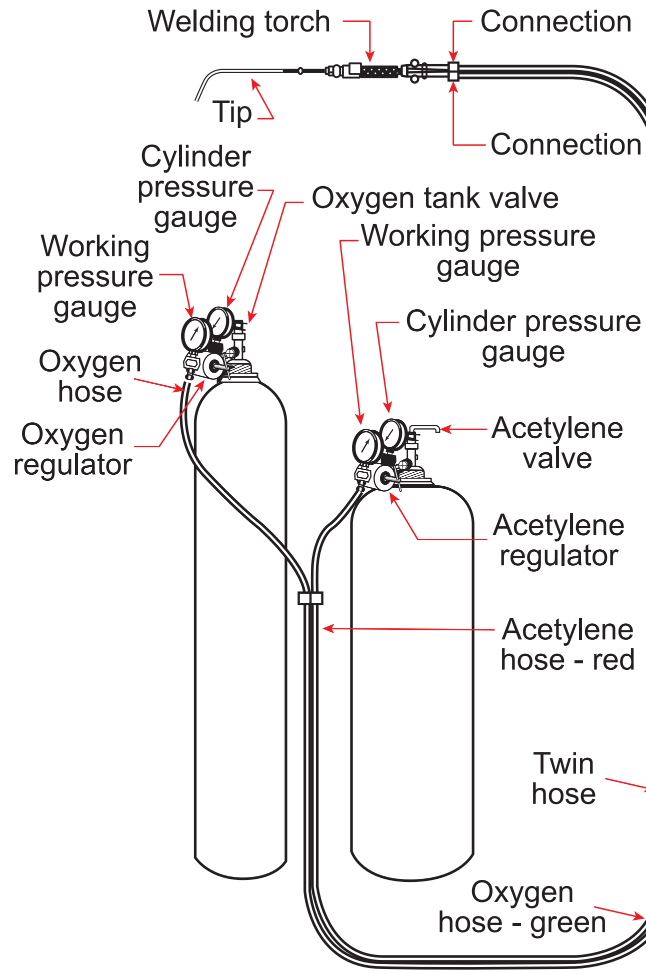
The Oxy-Fuel Welding Outfit

A typical oxyacetylene outfit consists of the following:

- An oxygen cylinder, which is tall and painted green or red
- An acetylene cylinder, which is short and painted red or black
- A set of gas pressure regulators: one for oxygen and one for acetylene
- A set of hoses to bring gas from the cylinders to the torch
- A welding torch
- A cutting torch
- A striker for lighting the torch

An oxyacetylene outfit is shown in Figure 2.

Figure 2 – Oxy-Fuel Outfit



CAUTION

Gas cylinders may explode if damaged.

a) Always keep cylinders in an upright position securely chained to a fixed support.

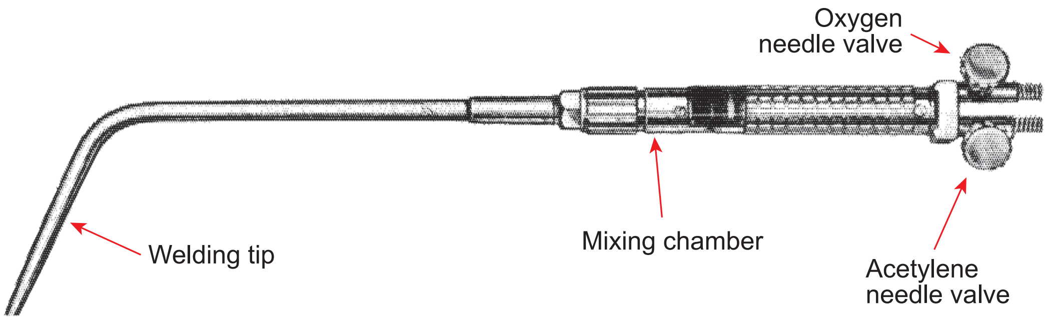
b) Locate cylinders away from areas where they may be exposed to physical damage, and at a safe distance from welding or cutting operations.

c) Keep valve protection caps in place and hand tight when the cylinder is not in use.

Oxy-Fuel Torch

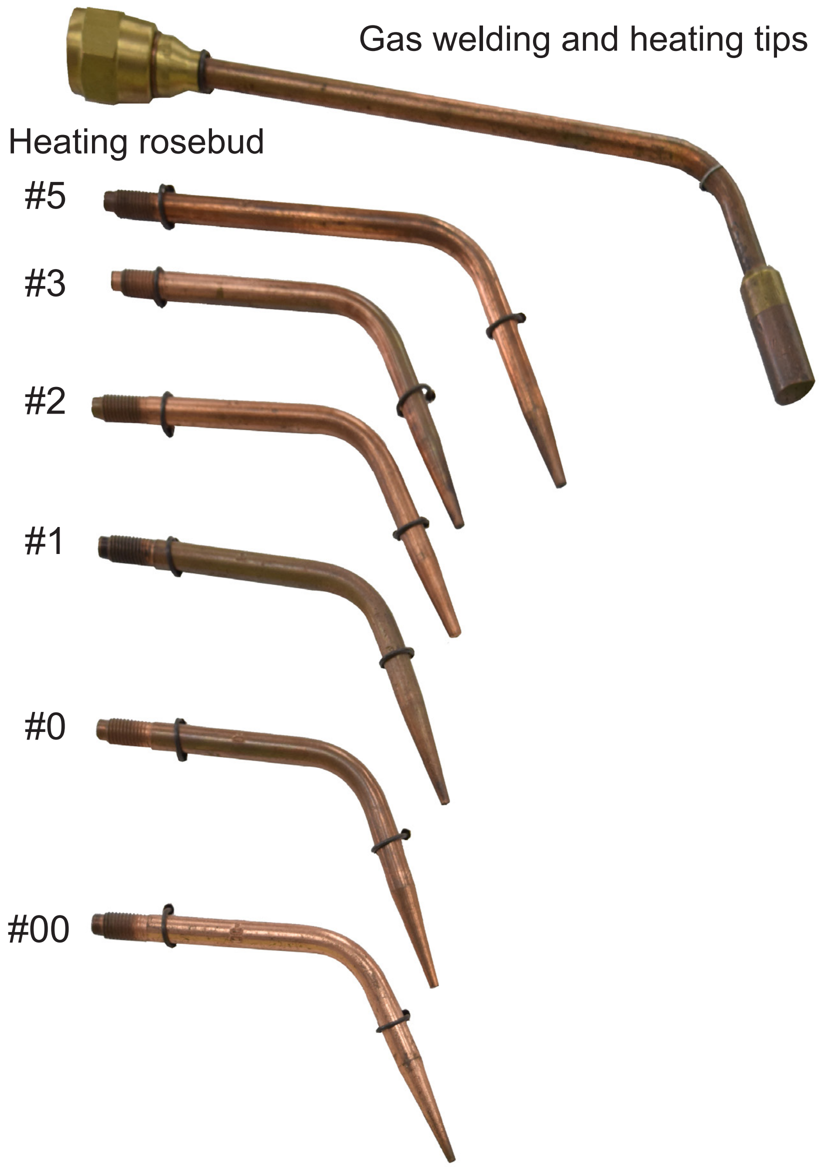
An oxy-fuel torch, which may be used with acetylene gas (Figure 3), consists essentially of a mixing chamber with oxygen and acetylene connections at one end, and a small nozzle at the other end. Each gas connection is fitted with a needle valve to control the flow of the gases. At the other end of the mixing chamber, a welding tip is attached. A variety of tip sizes supply different amounts of heat, in order to weld different metal thicknesses.

Figure 3 – Equal Pressure Oxy-Fuel Torch



The type of torch generally used in North America is the **Equal Pressure Torch**. The torch tips are numbered to indicate the required fuel and oxygen pressures. For example, a number two tip requires two psi (14 kPa) of both oxygen and acetylene. Likewise, a slightly larger number five tip requires about five psi (35 kPa) of oxygen and acetylene. To weld thicker material, a larger tip size is used. Figure 4 shows a number of interchangeable welding tips of different sizes.

Figure 4 – Welding Tips



Oxy-Fuel Gases

Acetylene (C_2H_2) is the most commonly used fuel with OFW. Acetylene is also a very unstable gas. At pressures above 103 kPa (15 psi), it can readily decompose into an explosive mixture of carbon and hydrogen. To safely store acetylene gas in a pressurized cylinder, the acetylene must be dissolved in liquid acetone. Therefore, the acetylene cylinder must contain acetone. As well, the acetylene cylinder contains a porous filler material, to keep the acetone from sloshing around.

CAUTION

Due to its instability, it is dangerous to supply acetylene to a welding or cutting torch above 100 kPa pressure (15 psi).

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Oxygen is a non-combustible gas. However, oxygen is a powerful oxidizer. It can promote vigorous (or even violent) combustion.

CAUTION

Combustible materials like oil and grease may ignite or explode in the presence of concentrated oxygen, even if an ignition source is not present. Even materials that do not burn in a normal atmosphere may burn in an oxygen-enriched atmosphere. Therefore, oxygen must be handled carefully.

Pressure Regulators

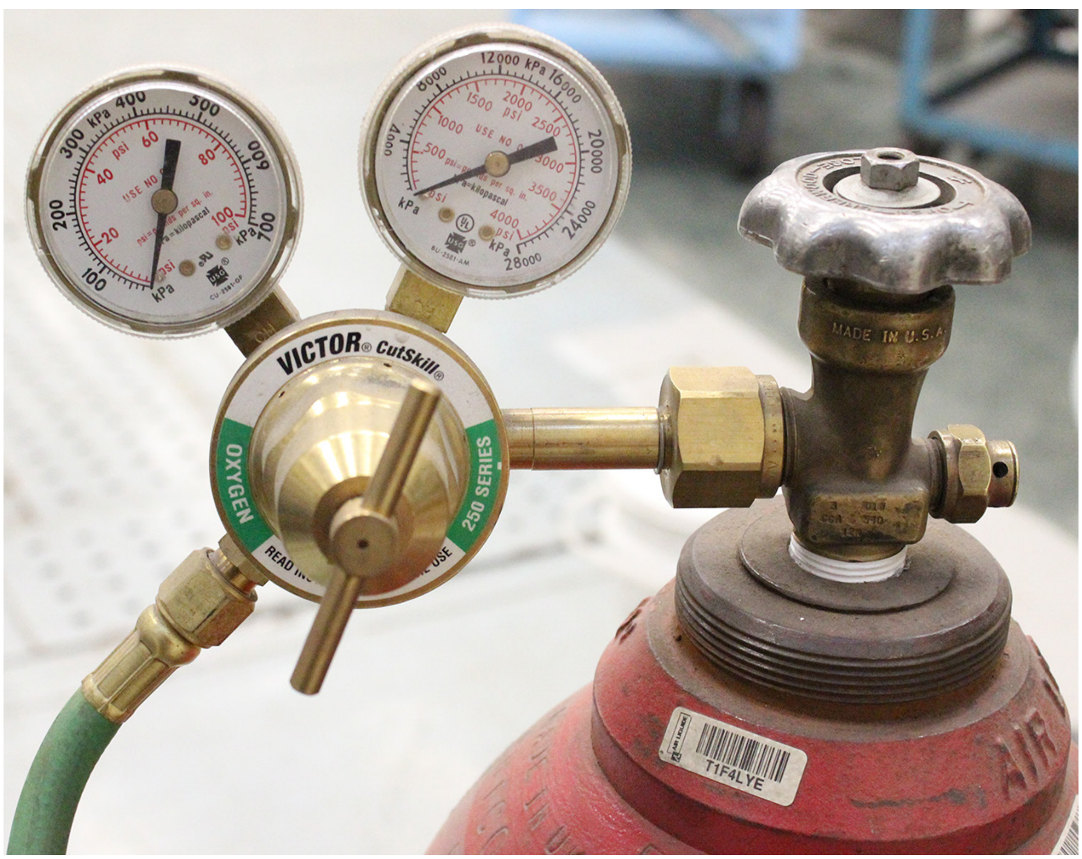
A fully charged oxygen cylinder has a pressure of about 15 000 kPa (2175 psi). A fully charged acetylene cylinder has a pressure of about 1725 kPa (250 psi). This is far more pressure than brazing, welding, or cutting requires. Both the oxygen and acetylene pressures are reduced to the required pressure with pressure regulators.

Each regulator has two pressure gauges. The first shows the cylinder pressure. The second shows the pressure supplied to the torch. Each regulator is equipped with a knob for adjusting the gas supply pressure.

The acetylene regulator is designed to regulate the supply pressure to less than 100 kPa. It often has a warning on the face of the gauge to not exceed this pressure.

Oxygen regulators have supply gauges calibrated 0-1035 kPa (0-150 psi), 0-1380 kPa (0- 200 psi), or 0 - 2760 kPa (0 - 400 psi). The high-pressure oxygen regulators are designed to supply enough pressure and volume to cut thick steel. Figure 5 shows a typical oxygen pressure regulator with gauges.

Figure 5 – Oxygen Pressure Regulator with Gauges



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Oxygen and acetylene regulators are not interchangeable. To ensure the oxygen regulator is not accidentally connected to the acetylene cylinder, the oxygen cylinder and regulator have right hand threads. Acetylene cylinders, regulators, and hose connections have left hand threads, and are marked by cuts in the connecting nuts.

The oxygen cylinder and regulator threads may accumulate dirt and debris. It is imperative that these threads be kept clean of any combustible material, especially lubricating and penetrating oil.

CAUTION

Pressurized oxygen can and will cause combustible materials to ignite without the presence of an ignition source. Do not use any oily product on the oxygen regulator or pressure gauge threads.

Each gas cylinder is equipped with a shut off valve and a threaded cap to protect the valve when a gas pressure regulator is not attached.

Hose sets

The welding/brazing torch is connected to the cylinders by hoses of two different colours. The green hose supplies the oxygen. The red hose supplies the acetylene.

A special flame arrestor fitting must be installed in the gas supplies to the torch to prevent explosive flash back. Modern welding torches often have flashback arrestors built into the torch itself.

Oxyacetylene Cutting

A cutting torch is commonly found in an OFW outfit. A cutting torch may be a complete, separate item with its own handle and valves. However, welders frequently choose to use combination torches, which can be converted from welding to cutting by changing the welding tip to a cutting head.

Oxyacetylene cutting is limited in use to ferrous metals. Steel and iron can both be cut using a cutting torch; however, cast iron is much more difficult to cut than mild steel. Stainless steel and aluminum cannot be flame cut, because they rapidly form heat resistant oxides when exposed to flame. To flame cut stainless steel, a plate of mild steel (called a “waster plate”) may be clamped to the surface of the stainless plate. The cutting torch is applied to the mild steel plate, and the stainless plate melts into the shape of the cut made to the mild steel.

Often, oxyacetylene cutting is called “flame cutting”, though this is inaccurate. In reality, the steel or cast iron burns in a stream of pure oxygen. For this to occur, steel must first be heated to a temperature of 870°C. A thin oxygen jet is then directed to the hot steel, and it quickly burns to produce a narrow cut. To cut steel plate, normally 20 kPa acetylene and 280 kPa oxygen would be used. The oxygen pressure would be increased or decreased to suit the thickness of the plate being cut.

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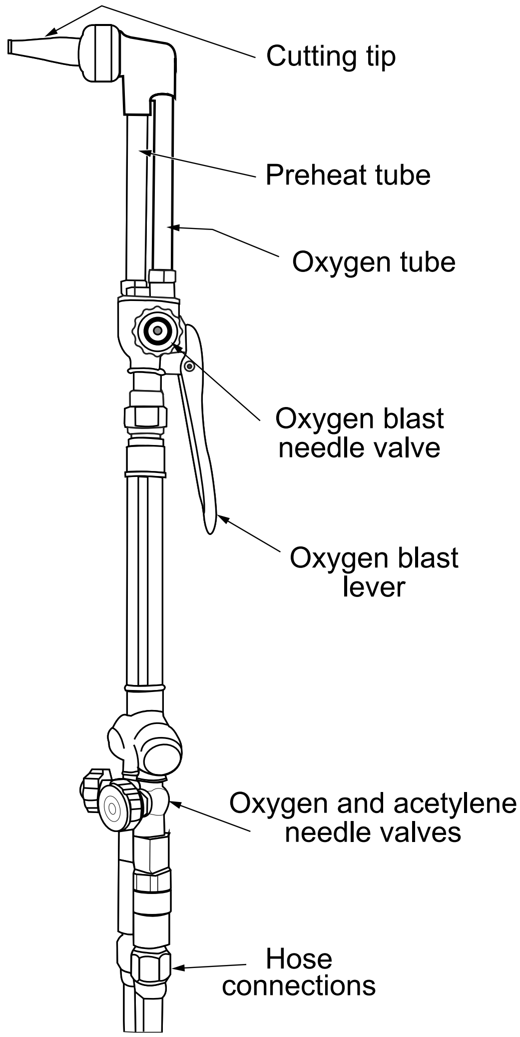
Figure 6 shows a cut-away of a cutting torch. Note the cutting handle valve, which permits high-pressure oxygen to jet from the cutting tip.

Figure 6 – Cutting Torch (Oxyacetylene)



Objective 3

Describe metal arc welding processes.

This objective will examine the most common arc welding processes recognized by ASME for the construction of boilers, pressure vessels, and pressure piping.

- SMAW
- GMAW
- GTAW
- SAW

Metal Arc Welding Processes

The ASME defines arc welding as: "*a group of welding processes wherein coalescence is produced by heating with an arc or arcs, with or without the application of pressure, and with or without the use of filler metal.*"

The heat to melt the parent metal is obtained from an electric arc formed between the base metal and an electrode. The temperature produced by the arc ranges from 3000°C to 8300°C, resulting in a molten metal "puddle" at the location of the arc. The puddle "moves" in location as the electrode tip proceeds across the weld joint surfaces.

CAUTION

a) The electrode and work pieces are electrically "hot" when the welding machine is "on." Do not touch "hot" parts with bare skin or wet clothing.

b) Electric arcs give off intense ultraviolet energy that can burn. Use eye protection with a protective filter to protect your eyes from the arc and sparks when arc welding or observing arc welding. Use suitable clothing made from durable flame-resistant material to protect your skin.

c) Protect by-standers with non-flammable screening and warn them not to watch the arc.

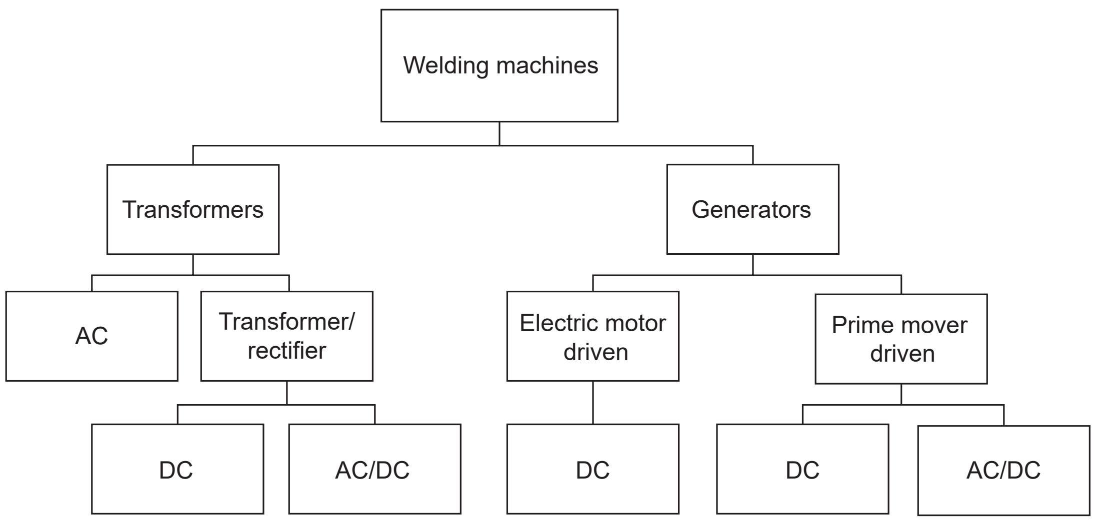
Shielded Metal Arc Welding (SMAW)

SMAW (often called "**stick welding**" or "arc welding") is the most common welding process in the world. It has been an acceptable method for manufacturing boilers and pressure vessels since the 1930s, when improvements made the process more reliable. Like OFW, SMAW is a fully manual welding process, though it requires the use of only one hand.

Power Supplies

SMAW uses a DC or AC electric power supply to provide heat energy to melt the parent metal. The electrical energy is converted into heat when an electric current passes from the weld electrode to the parent material in the form of an arc. The amount of heat generated depends on the current flowing in the circuit, which the welder can vary. More current produces more heat, and less current less heat. More current is needed when thicker metal is being welded, and greater weld metal deposition rates are needed. Figure 7 shows the main categories of welding machines.

Figure 7 – Types of Welding Machines

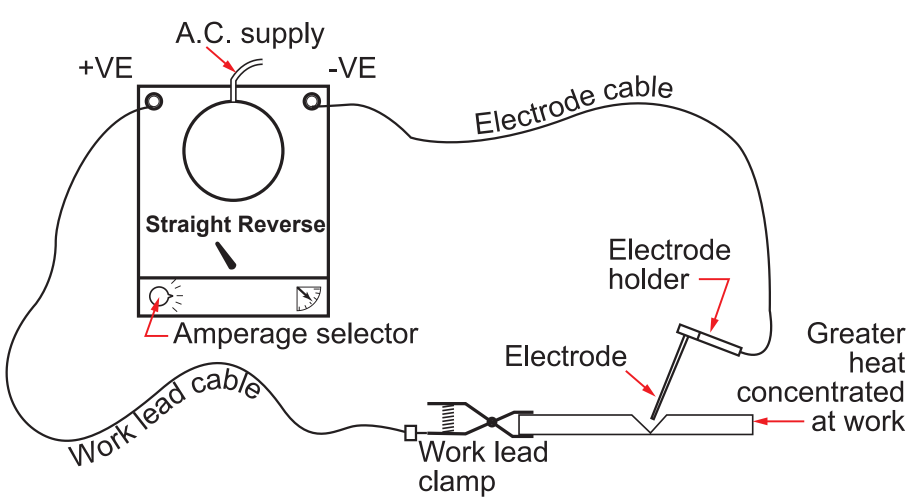


SMAW power can be provided by either generators or transformers. Both generators and transformers are capable of supplying AC, DC, and AC/DC, depending on the machine. DC power is supplied either as **DC electrode negative** (**DCEN** or "**straight polarity**"), or **DC electrode positive** (**DCEP** or "**reverse polarity**"). See Figures 8 and 9.

Note that the work piece and electrode connections are opposite in each diagram. DC current flows in one direction only, resulting in the best control of the welding process, and the best quality welds. For this reason, DC machines, or machines capable of supplying DC, are usually preferred to AC machines.

Figure 8 – DCEN ("Straight Polarity")

(20)



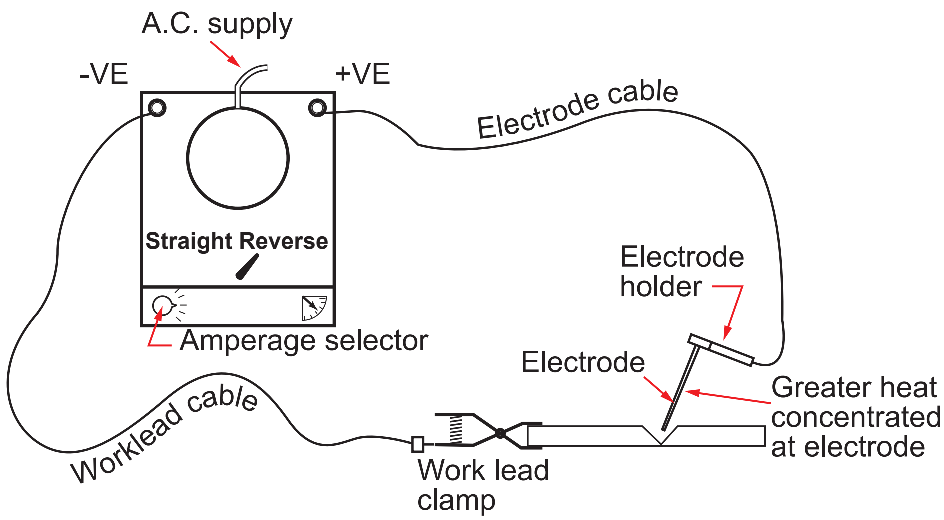
The choice of DCEN or DCEP depends upon the type of welding job being done and the electrode being used. With DCEP, about 2/3 of the heat energy is concentrated in the electrode. This causes the electrode to melt faster, which produces higher rates of weld deposition and faster welding speeds.

DCEP is preferred where shallow, wide weld deposits are preferred. On the other hand, with straight polarity, about 2/3 of the heat energy is concentrated in the parent metal. The electrode melts more slowly in this case, resulting in slower welding speeds. Weld penetration tends to be deeper and the weld deposit width is narrower.

DCEP is preferred when doing overhead welding, where the filler metal from the electrode must solidify quickly to prevent it from falling away from the work.

Figure 9 – DCEP ("Reverse Polarity")

(20)



The function of any transformer is to change voltage and current from one set of values to another. A welding transformer changes line voltages and currents to values suitable for welding, and supplies this power to the electrode and work pieces.

The person performing the weld can change the current using a control knob or handle, depending on the weld procedure being used. If the machine can supply DC power, the AC power supplied to the machine is first transformed, and afterwards rectified to DC. DCEN and DCEP may be selected by a knob or lever on the transformer control panel, or by physically changing the electrode and work piece connections to the machine.

Welding generators may be gas, diesel, or electric. As the name implies, they consist of a motor directly coupled to a welding generator. The generator supplies the electrical current and voltage for welding.

The main advantage of prime-mover driven welding generators is that they are portable. Often, they are mounted on a truck or trailer, making them suitable for remote pipeline use. Though some provide both AC and DC, most of the larger truck or trailer mount generators supply only DC. This is not considered a disadvantage, because industrial welders prefer DC welding to AC.

Electrodes

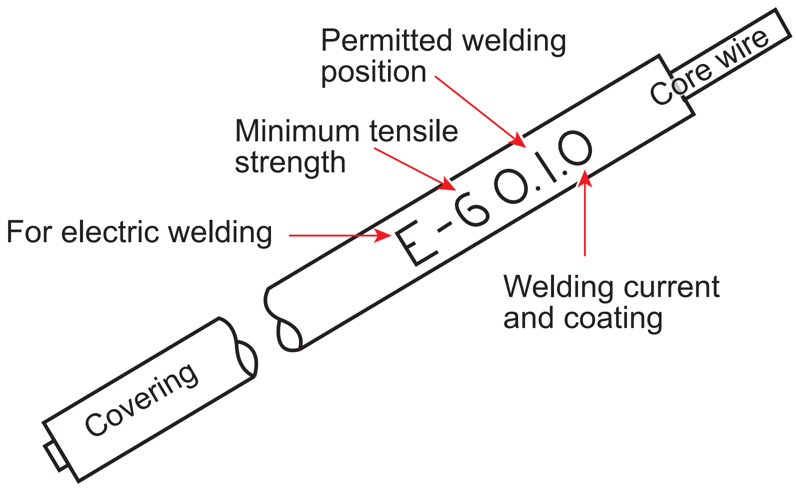
The electrode used for SMAW is made of a wire core covered with a coating. The wire core material is the same metal as the parent metal. While welding, the electrode wire melts and mixes with the molten parent metal in the weld puddle. For this reason, the electrode is called a **consumable electrode**. Because, the electrode metal combines with the parent metal, the electrode metal is also referred to as filler metal. All SMAW is performed with filler metal.

Electrodes for SMAW (also called "**filler rods**") are coated with combustible or mineral materials. If the coating is of combustible material, the electrode is best suited for DC. Mineral-coated electrodes may be used for AC and DC welding.

The combustible type of electrode coating protects the weld puddle by thermally decomposing, thereby producing a gaseous envelope ("**shielding gas**") around the weld. This gaseous envelope keeps oxygen, hydrogen, and moisture away from the weld puddle as it solidifies, thereby preventing **porosity** ("bubbles"), brittleness, and oxidation of the weld. The mineral-coated electrode types give protection by forming a slag coating on the weld puddle. The slag acts as insulation against the air while cooling takes place. The electrode coverings also aid in stabilizing and directing the arc, and to a very large degree, determine the welding characteristics of the electrode.

The **American Welding Society** (**AWS**) has developed specifications and identification numbers for **shielded metal arc welding** rods as shown in Figure 10.

Figure 10 – AWS Identification of Coated Electrodes (SMAW)



SMAW electrodes are stamped near one end so that the electrode is identifiable, even after the electrode is completely consumed (Figure 10). All SMAW-suited electrodes are stamped with the letter "E", which shows that the rod is suitable for electric arc welding. All AWS approved rods have a four-digit code that follows the letter "E".

The first two digits of AWS certified welding electrodes give the minimum tensile strength of the wire core material, in ksi (1 ksi = 1000 psi). So, if the first two digits are "60", the tensile strength of the wire core is 60,000 psi.

Electrodes that meet the marking requirements of the **Canadian Welding Bureau (CWB)** are required to meet **CSA Standard CSA W48**. For these electrodes, the first two digits after the letter "E" indicate the tensile strength of the wire core in 10^7 Pa. So, a weld electrode with the first two digits "43" would have a tensile strength of 43×10^7 Pa, or 430 MPa.

Because 60,000 psi nearly equals 430 MPa, an AWS rod stamped "E60" is considered the same as a CWB/CSA rod stamped "E43". It is important to select an electrode with a tensile strength at least as great as the parent material.

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Table 2 is a cross-reference for electrodes that meet both AWS and CSA standards. Note that most Canadian welders refer to an electrode by its AWS designation rather than its CSA designation.

Table 2 – Comparison of CWB/CSA and AWS Electrode Designations

CWB/CSA W48 Electrode	Equivalent AWS Electrode
E43XX	E60XX
E49XX	E70XX
E55XX	E80XX

Regardless of whether AWS or CSA electrode designation system is used, the digit that follows the tensile strength indicates the weld position the rod may be used in.

1 = All positions

2 = Flat or horizontal

3 = Flat only

4 = Down hand only

The last digit is a guide to the rod's characteristics (coating, current type, and penetration).

For example, consider an electrode stamped E4914 (E7014). This is a general-purpose rod that is suitable for welding thinner metal, in any position. It must NEVER be used for dynamically loaded structures or pressure vessel construction. Beginners find this rod easy to weld with, so it is sometimes called a "High Heat—Low Talent" rod. It has a mineral coating of **rutile** (titanium dioxide) and iron. The rod may be used with AC, DCEP, or DCEN. It is capable of medium penetration.

The weld electrode is placed in an electrode holder, often called a "**stinger,**" which is connected to the power supply by a heavy insulated cable. The parent metal is also attached to the power supply by means of a cable and a spring clamp (Figure 11a). On machines with polarity switches, the work piece cable must be connected to the welding machines "to work piece" connection, and the electrode holder must be connected to the welding machine's "electrode" connection. Then, switching polarity is accomplished by merely moving a lever.

Figure 11(a) shows a complete SMAW welding circuit. The detail of the arc is shown in Figure 11(b). In this figure, the weld is progressing from the left to the right. Note the decomposition products of the electrode coating: a gaseous shield, and a slag coating. Together, they protect the weld metal as it solidifies and cools.

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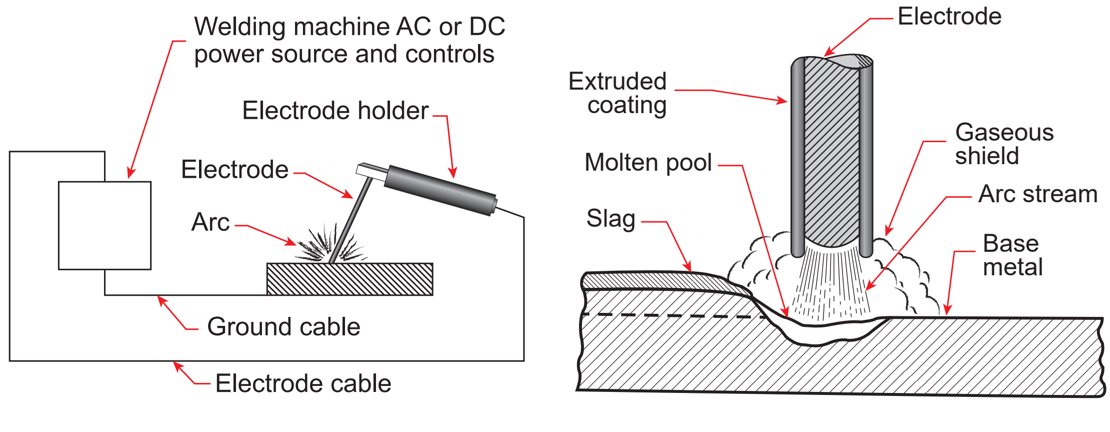
Figure 11 – SMAW



(a) (b)

Gas Metal Arc Welding (GMAW)

Commonly called "**MIG**" welding (**metal inert gas welding**), GMAW may be a **semi-automatic arc welding** process, or it may be fully automatic ("robotic" welding). As a semi-automatic process, the welder controls the rate of weld progression, but the welding machine controls the rate of electrode addition. GMAW is faster and cleaner than SMAW, and capable of producing pressure-vessel quality welds.

GMAW was originally developed for welding aluminum and other non-ferrous materials in the 1940s. It was soon applied to steels because it allowed for faster welding compared to other processes. The cost of inert gas limited its use in steels until several years later, when the use of gases such as carbon dioxide became common.

With GMAW, a continuous consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used.

Unlike SMAW, with GMAW there is no need for a welder to intermittently stop and replace filler rods, so welding jobs take less time to complete. Without the "stops and starts" for electrode changes, there is less likelihood that weld **defects** such as crater cracking and arc strikes will occur.

There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray, and pulsed-spray. They each have distinct properties and corresponding advantages and limitations.

GMAW is used in industries such as the automobile industry, where it is preferred for its versatility and speed. Unlike welding processes that do not employ a shielding gas, such as SMAW, it is rarely used outdoors.

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Gas Tungsten Arc Welding (GTAW)

Gas tungsten arc welding (GTAW), also called **tungsten inert gas** (TIG) or "**Heliarc**" welding, is a fully manual arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas, such as argon or helium. A filler metal is normally used, though it is not necessary in some instances. A constant-current welding machine provides power for the arc, which takes place through a column of highly ionized gas and metal vapours known as plasma.

GTAW is most often used to weld thin sections of stainless steel and light metals such as aluminum, magnesium, and copper alloys. This process gives the operator greater control over the weld than other processes such as shielded metal and **gas metal arc welding**, thus allowing for stronger and higher quality welds. However, GTAW is comparatively more complex and difficult to master, and it is significantly slower than most other welding techniques.

Submerged Arc Welding (SAW)

SAW is a fully automatic arc welding process. A machine which has been programmed by a **welder operator** controls both the rate of weld progression and the rate of filler material admission. The electric arc occurs invisibly, beneath a protective layer of granular and molten mineral flux. Submerged arc welding produces seams which are neat and uniform in appearance, and impossible to imitate by manual or semi-automatic welding.

With SAW, the weld puddle is shielded similar to the way the puddle is shielded by SMAW. Rather than using a coated electrode, the shielding material is continuously fed to the weld region in granular form. The shielding material is known as the melt, flux, or welding composition. The term flux is the most common one used, although the fusible material serves other purposes.

During the welding process, the flux becomes molten due to the extreme heat. Because the arc between electrode and parent metal travels through the molten flux, the arc is not visible to the welder operator. Very little gas or fumes rise from the weld.

Starting the arc may be accomplished in several ways. One way is to put a piece of steel wool between the electrode and the work-piece before switching on the electrical power.

A submerged arc welding apparatus is shown in Figure 12. As seen in the diagram, granular flux is deposited on the weld joint ahead of the electrode's direction of travel. The arc is struck underneath the flux which, although a nonconductor when cold, becomes highly conductive when molten at about 1310°C.

This forms a path for the current and the generated heat keeps the flux molten. The welding operation takes place beneath the flux without sparks, spatter, smoke, or flash; thus, there is no need for protective shields or helmets.

The molten flux, which is lighter than the weld metal, rises to the surface of the weld and solidifies as a glass-like covering for the weld bead. It protects the weld from oxidation, slows its rate of cooling, and produces a smooth, well-shaped bead. The cold flux is easily removed. Often, it pops off the solidified weld bead spontaneously. Excess flux can be recovered and reused after proper processing.

Either DC or AC may be used. The welding machines may be of either the conventional drooping voltage characteristics or constant voltage type. There are advantages to the use of each of these types of current supply, dependent upon the application.

With constant voltage, the arc length is self-adjusting. If a machine has drooping voltage characteristics, a voltage sensitive relay adjusts the wire feed to maintain the desired arc length. Two electrodes may be employed simultaneously, working in series or parallel. Each electrode may even have its own power supply. Welding currents may be as high as 4000 amps, though commonly no more than 2000 amps would be used.

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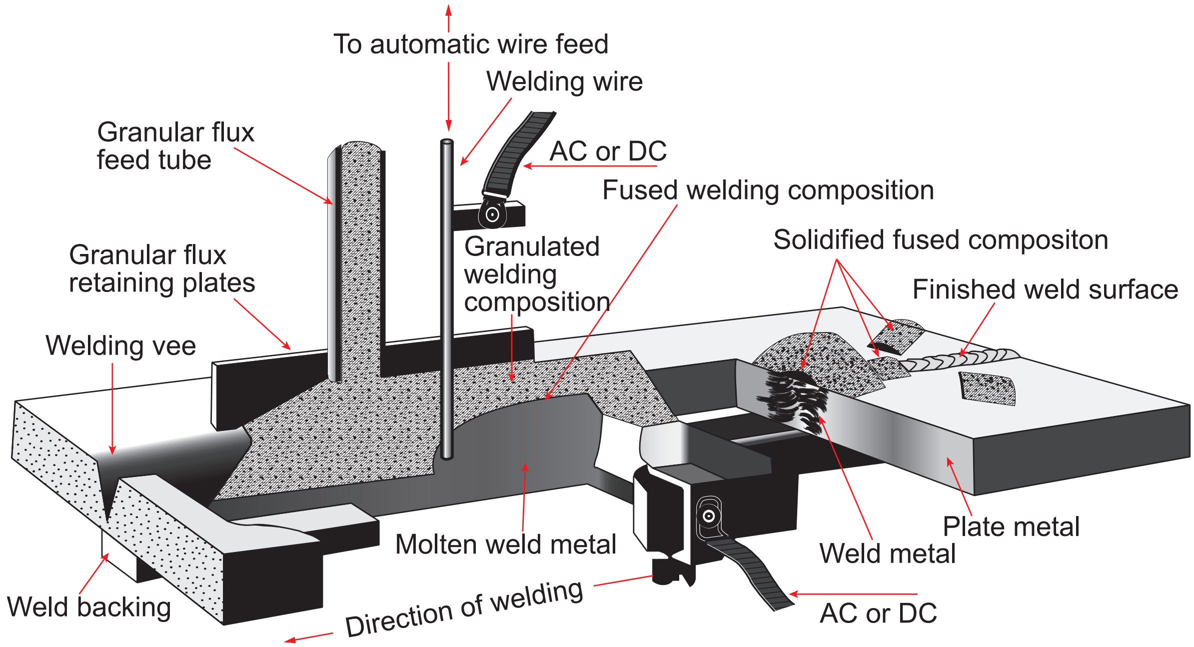
Figure 12 – Submerged Arc Welding with Granular Flux Shielding



Objective 4

Describe heat treatment of welds.

Heat Treatment

Heat treatment refers to a number of different procedures performed on various metals to improve their mechanical properties, or to regain their mechanical properties after undergoing a process like flame cutting, welding, or bending. Heat treatment includes procedures like **post weld heat treatment** (**PWHT**), **stress relief**, tempering, annealing, normalization, and **preheating**. This objective will cover post weld heat treatment (PWHT) and preheating. Other heat treatment processes will be covered at higher levels of Power Engineering studies.

Post Weld Heat Treatment (PWHT) or Stress Relief

In the early days of steel fabrication, blacksmiths learned not only how to make steel from iron and carbon, but how to make steel harder by first heating and then quenching (rapidly cooling) it. When making cutting tools, blacksmiths would heat the finished steel form until red hot, and then immediately quench it in water. In doing so, the steel cutting tool would become much harder than it was previously. Then, it could be sharpened, and it would hold its edge for a long time.

However, the heating and quenching also made the cutting tool brittle, so that it would crack or shatter if delivered a sufficient blow. To make hardened steel tough, flexible and to restore its ductility, blacksmiths would reheat the hardened cutting tool to a somewhat lower temperature than before, and allow it to cool slowly, in a procedure known as "tempering."

When steel is welded, the weld metal is heated and quenched like the blacksmith's cutting tool. The parent material at the weld joint is heated so hot that it melts. The un-melted parent metal adjacent to the weld becomes red hot. The entire weld joint, including the red-hot parent metal adjacent to the weld joint, is called the "**Heat Affected Zone**" (**HAZ**).

The parent metal is unaffected by the heat and remains relatively cool. It rapidly draws heat away from the HAZ, quenching it. The result is that the entire HAZ – comprised of deposited weld metal and the adjacent parent metal – becomes hard and brittle.

Brittle materials may be very strong and very hard, but they break without showing prior deformation. Deformation gives warning that a solid ductile material is approaching its ultimate strength. Imagine a balloon that bursts without first expanding in size. Boilers or pressure vessels are like balloons: if their welds are brittle, they can fail suddenly, with no prior warning, which will lead to disastrous explosions.

The tempering concept the blacksmith used is applied to welded boilers and pressure vessels, as a procedure called "post weld heat treatment" (PWHT) or "stress relief." The ASME codes give instruction on how to successfully post weld heat treat weld joints for boilers, pressure vessels, and pressure piping. For example, **ASME Code Section 1, paragraph PW-39** requires newly constructed boiler shells to be placed in a furnace and heated to above 595°C. The temperature must be held one hour for every 25 mm of thickness. After heating, the boiler shell is cooled at a slow, controlled rate, so that "quenching" does not re-occur.

These furnaces must be large enough to accommodate entire boiler shells or piping systems. Portable equipment, like handheld torches are used to stress relieve equipment fabricated or welded on site, such as piping systems.

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Preheating

Blacksmiths also learned that the hardness of quenched steel depended on how fast it cooled. If red-hot steel was slowly cooled in air, it would not become hard. If steel was oil-quenched, it would be harder than if cooled slowly in air, but not as hard as water-quenched steel. The same principle applies to preheating weld joints.

To prevent rapid cooling of the HAZ during welding, the entire area surrounding the weld joint can be preheated in a furnace, or with hand-held torches. The preheat temperature may range from 80°C to about 230°C depending upon the type of steel and its thickness. As a result, the HAZ cools at a slower rate, due to the diminished temperature gradient between the HAZ and the parent metal. The slower cooling rate results in welds that are more ductile.

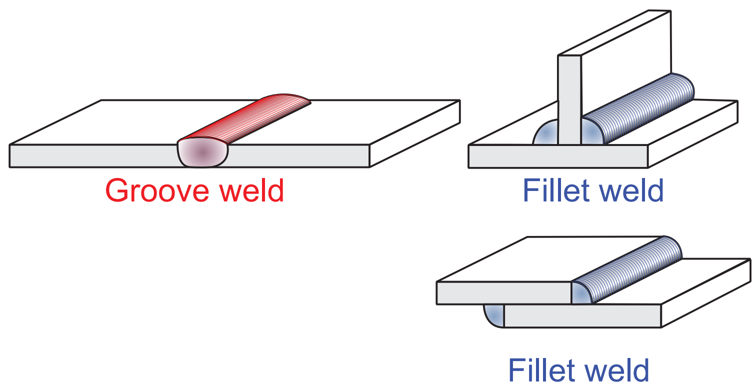
Objective 5

Describe the types of weld joints used in pressure vessel construction.

Weld Joint Categories

Weld joints fall into two broad categories: **groove welds** and **fillet welds**. Fillet welds all have parent material ("**backing material**") behind the weld puddle. This backing material makes it easier to perform fillet welds than groove welds, because the backing material keeps the heat of the arc from burning through the parent metal.

Figure 13 – Weld Joint Categories



Fillet welds are used to construct the "**tee joints**" and "**lap joints**" (Figure 13), both of which are used in the manufacturing of boilers and pressure vessels. Tee joints are used to attach nozzles and firetube tubesheets to boiler shells. Lap joints are used to reinforce vessel openings with **repads** (Figure 14).

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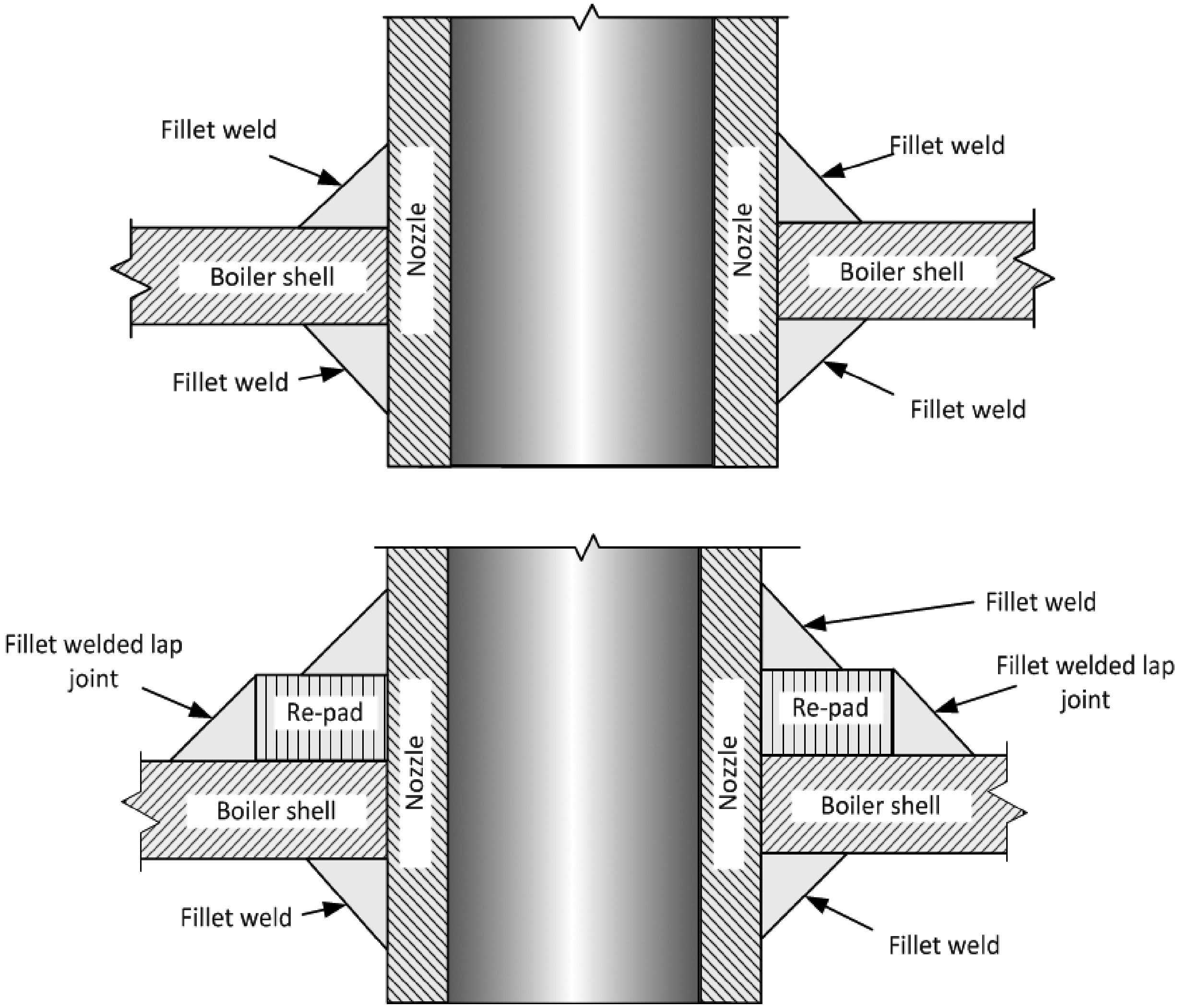
Figure 14 – Fillet Welds used for Tee and Lap Joints in Boiler and Pressure Vessel Construction



Groove welds connect work pieces that have their thicknesses centred in-line. The simplest groove weld is the **butt joint**. The parent metal pieces being joined are first machined so that their edges are smooth, and match in contour.

The only preparation necessary is to ensure that the edges are clean, free of oil, and free of dirt and paint. The work pieces are then set apart by the approximate thickness of the welding rod being used. Small short welds are made to hold the work pieces in position while the material is being welded. These small welds are called "**tack welds**."

The work pieces can be welded from one side of the material, or from both sides. If welded from one side, the weld joint is referred to as "**single-welded**." If welded from both sides, the weld joint is called "**double-welded**." Double-welded joints are used for thicker parent materials (Figure 15).

Thicker material requires more joint preparation, especially if the joint can only be accessed from one side of the parent metal. **ASME 1 PW-9.1** states:

> *"Longitudinal, circumferential, and other joints, uniting the material used for drums, shells, or other pressure parts … shall be full penetration butt welds. The welds should preferably be of the double-welded butt type, but may also be of the single-welded butt type with the filler metal added from one side only when made to be the equivalent of the double-welded butt joint by providing means for accomplishing complete penetration."*

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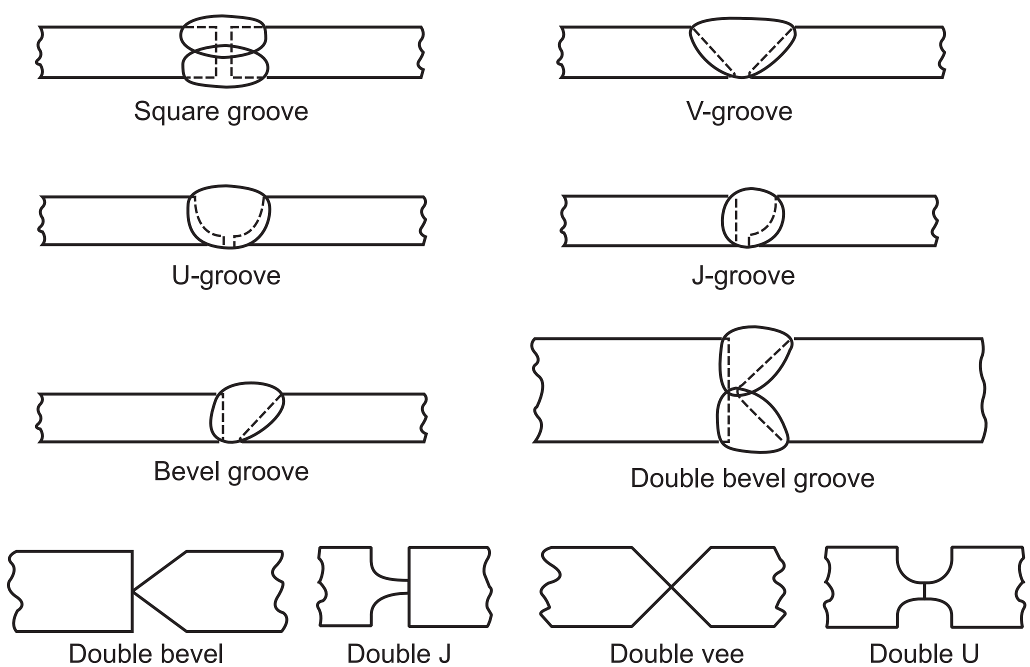
The *"means for accomplishing complete penetration"* – in other words, weld groove preparation - permits the deposition of a good quality root **pass**, which is essential for weld joint integrity. Without proper weld joint preparation, the welding electrode may not be able to reach all the way to the root of the weld ("full penetration"). The poor quality root will negatively affect the resulting completed weld joint.

Figure 15 shows a number of suitable groove preparations for achieving full penetration. The weld joint surfaces are manually machined using hand-held grinders, or automatically machined to specific dimensions. The square groove is used for thinner material. Because the material is somewhat thick, and minimal joint preparation was specified, the welder could not achieve full penetration from only one side. Therefore, this joint was welded from both sides, thus achieving full penetration.

The "V-groove" shown in Figure 15 is the most common form of weld preparation used. It allows full penetration from only one side of the material. This form of weld joint preparation is used for welding lengths of high-pressure pipe, and for boiler and pressure vessel repairs, when the material is only accessible from one side.

The double-welded joints shown in Figure 15 are used for very thick parent material. Compared to single-welded joints of the same thickness, double-welded joints reduce parent material distortion and residual stress. Double-welded joints significantly reduce the quantity of filler metal and other weld consumables used to fabricate the joint.

Figure 15 – Examples of Groove Preparation for Butt Welded Joints



Parts of a Weld

Figure 16 shows the details of a prepared groove weld. The groove angle is commonly 75 degrees for welded pipe. The **root face** is the part of the groove face that is not beveled. The purpose of the root face is to provide additional parent material at the root, thus helping to prevent burn-through. The **root opening** must be large enough to help full root pass penetration, but not too large as to permit burn-through.

Figure 16 – Groove Preparation Details and Terminology

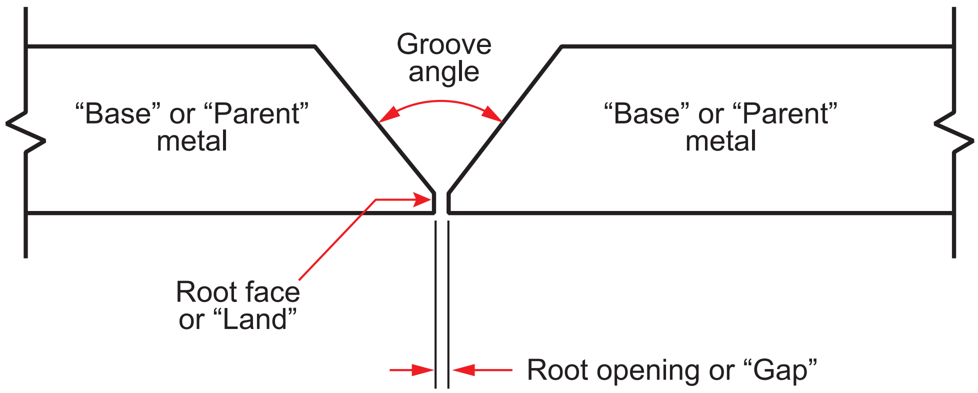


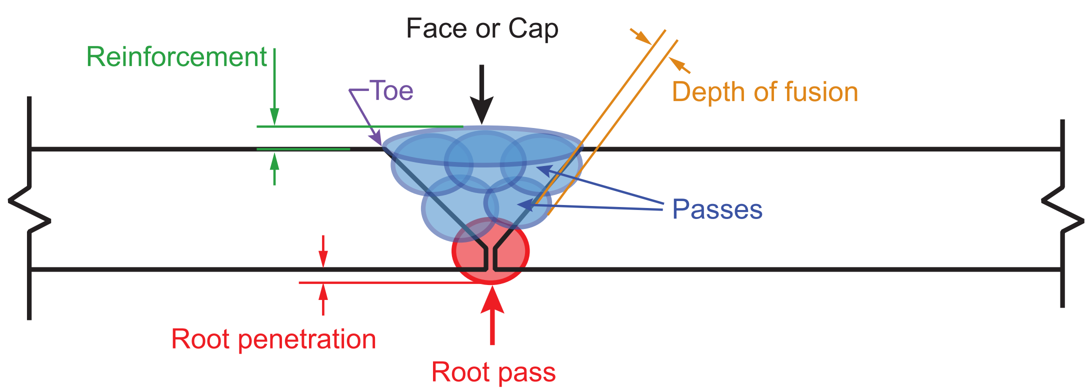
Figure 17 shows the details of a completed single-welded groove butt joint. The weld is a **multi pass weld**, meaning that the weld metal was deposited sequentially, layer after layer.

The weld in Figure 17 is made of seven passes. The first pass is known as the root pass, because it fuses the metal at the root of the joint. After each pass, the weld surface is cleaned of slag, so that slag particles do not become embedded in subsequent passes, thus weakening the joint.

Note that the root penetrates to the other side of the parent material, and actually extends a small distance to that backside of the weld. The distance the root extends to the back side of the parent metal is called the root penetration. The root must fully penetrate to the back side of the material, or the weld joint will not be as strong as the parent metal.

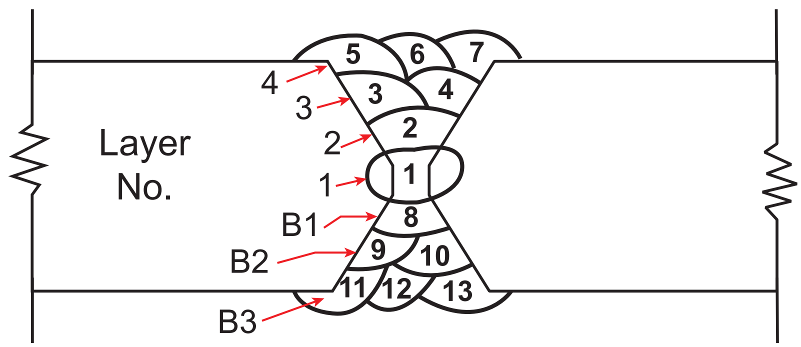
Notice that each pass melts into and combines with the parent metal. This is referred to as fusion. Every weld must have adequate depth of fusion, so that the weld metal joins with the parent metal. Also, note that each pass fuses with the preceding pass. This inter-pass fusion is important in making a strong weld.

Figure 17 – Details of a Single-Welded Multi-Pass Weld Joint



Double-welded joints are also multi-pass welds, as seen in Figure 18. Pass number one is the root pass. Passes numbered one through seven are welded from one side of the parent metal, and passes eight through thirteen are welded from the other side.

Figure 18 – Details of a Double-Welded Multi-Pass Weld Joint



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Objective 6

Describe the additional construction components required for pressure vessels to ensure structural integrity and "access."

Welded Boiler and Pressure Vessel Components

Since 1918, when the ASME first permitted fusion welding of boiler components, welding has proven to be the most reliable, durable, effective, and safest method of constructing boilers and pressure vessels.

Prior to welding's dominance, pressure vessels were fabricated using riveted construction. However, riveted joints could never be as strong as the parent metal plate.

Modern welded fabrication techniques, combined with modern quality assurance procedures, can produce joints that are as strong as, if not stronger than, the parent material.

Welded joints in boiler and pressure vessel construction may be:

- Strength welds in the pressure boundary of the vessel
- Strength welds in the non-pressure boundary of the vessel
- Seal welds

These welds may be tee-joints, lap joints, and butt joints, of any configuration permitted by the relevant ASME code section.

Pressure Welders

A certified pressure welder must perform all weld joints on a boiler's or pressure vessel's pressure boundary, whether during fabrication or repair, with no exception! Certified pressure welders must have thousands of hours of documented welding time, and must successfully pass one or more welding performance tests.

During the test, the welder must fabricate a weld joint, following a specific procedure. The weld joint is then cut into strips (called "coupons"), which are bent, pulled apart, and x-rayed, in accordance with the rules of **ASME IX**. If the coupons survive the destructive tests, and pass the non-destructive tests, the welder is certified to weld on boilers and pressure vessels following the procedure they used during the examination.

Pressure Boundary Strength Welds

The pressure boundary of a vessel refers to the metal components that directly restrain forces that arise due to the vessel's internal pressure. Any welding performed in the pressure boundary is critical to the strength, safety, and longevity of the boiler.

Examples of pressure boundary welds are:

- Longitudinal joints (Figure 19)
- Circumferential joints (Figure 19)
- Shell-to-head attachments (Figure 19)
- Nozzle-to-shell attachment (Figure 20)
- Tube-to-shell attachments (Figure 21)
- Firetube-to-tubesheet attachment (Figure 22)
- Manhole flue (reinforcing ring) attachment (Figure 23)
- Repad attachment (Figure 24)

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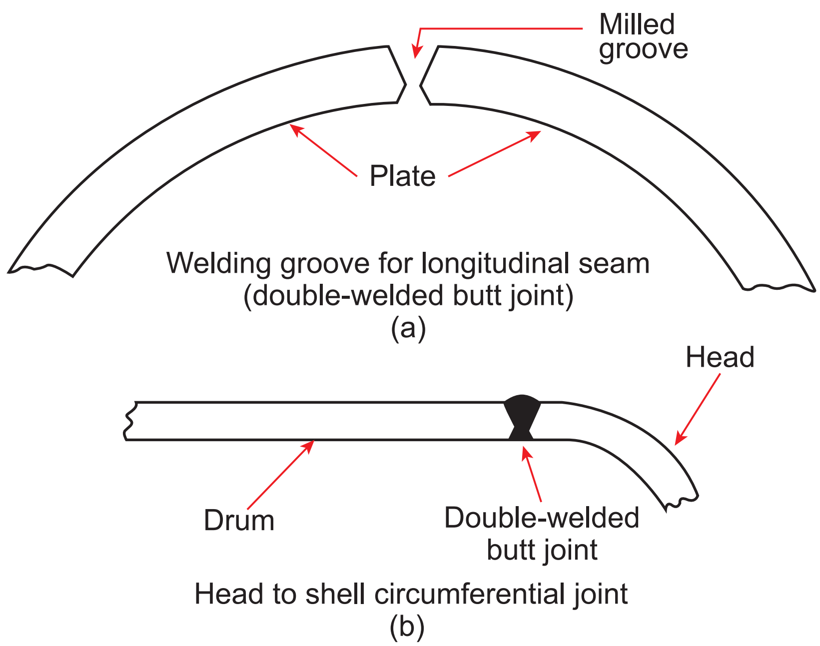
A strength weld is a weld designed to be as strong as the parent material. Each of the items listed above rely on the strength of the weld to ensure pressure vessel integrity.

Figure 19(a) shows a cross-sectional end view of a thick plate, rolled into a curved shape, so that the ends meet with a common centre-line. The weld joint was machined into a double vee groove, to facilitate welding from both sides.

Figure 19(b) shows a cross sectional side-view of a head-to-shell attachment. The fact that it is double-welded emphasizes that the material being used is quite thick.

Figure 19 – Longitudinal and Circumferential Strength Welds for Vessel Fabrication



Attachments

The welded nozzle attachments shown in Figure 20 demonstrate a number of ASME code acceptable methods of attaching nozzles to shells and headers. These nozzles may be used for attaching fittings such as:

- Safety valves
- Pressure gauges
- Water columns
- Water feeders
- Low water cut-offs

Other nozzles may be for:

- Feedwater piping
- Chemical feed piping
- Intermittent blowoff piping
- Continuous blowdown piping
- Steam outlet piping

These connection nozzles, or stubs as they are often called, are typically attached to the drum by welding. However, some lower pressure boilers have nozzles threaded (screwed) directly into the shell. The stubs may terminate with connections for attaching fittings or piping, using threaded attachments, welded attachments, or flanged attachments.

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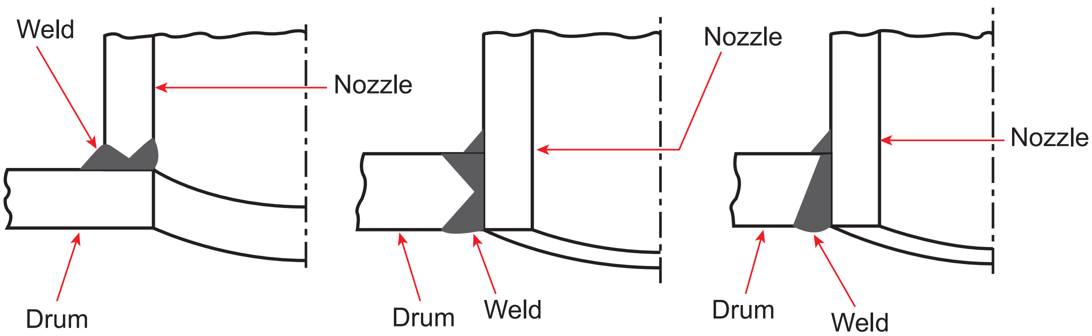
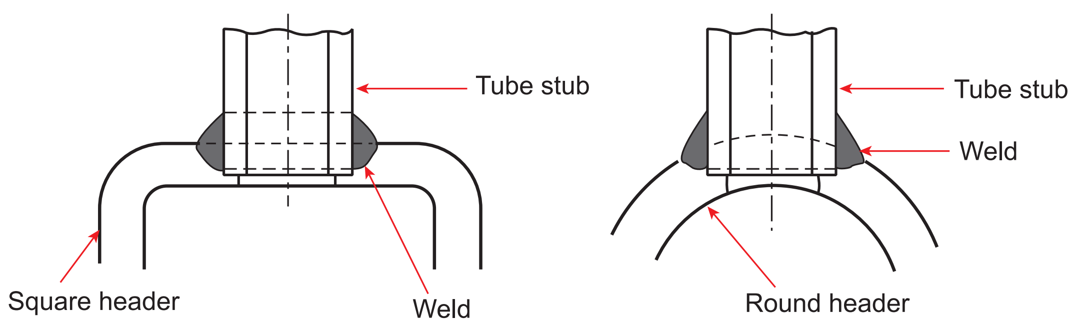
Figure 20 – Acceptable Nozzle to Shell Attachment



Tubes are often expanded into place; however, they may also be attached directly to the drum or shell using welded connections. Figure 21 shows tube stubs welded into place. First, the header is machined with a socket to accept the tube. The tube is cleaned and inserted into the socket. Groove welds are used to secure the tube stub in place.

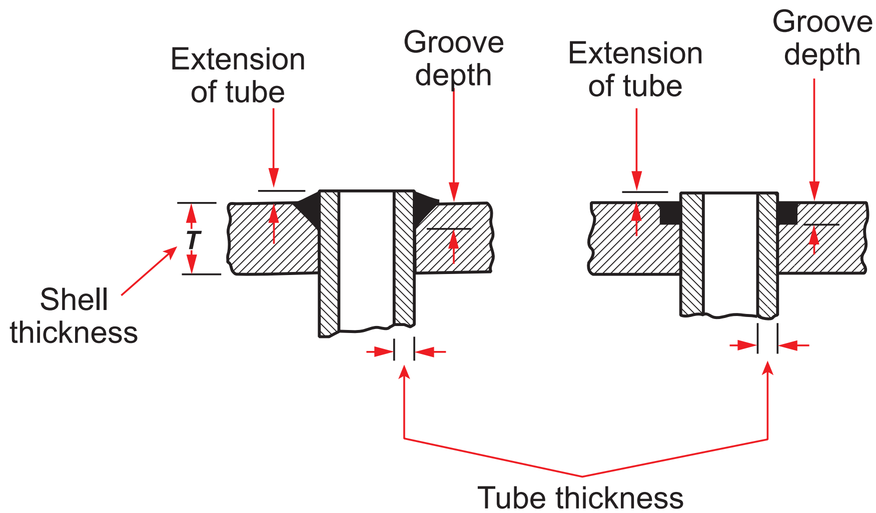
Such a sub-assembly is prepared in the fabrication shop, and then transported to a field location where the boiler is being erected. Watertubes (either risers or downcomers) are then butt welded using groove welds in the field.

Figure 21 – Acceptable Tube to Shell Attachment



Firetubes may be strength welded into place, instead of expanding. Figure 22 shows the two ASME code acceptable methods of attaching firetubes to tubesheets, using only strength welding.

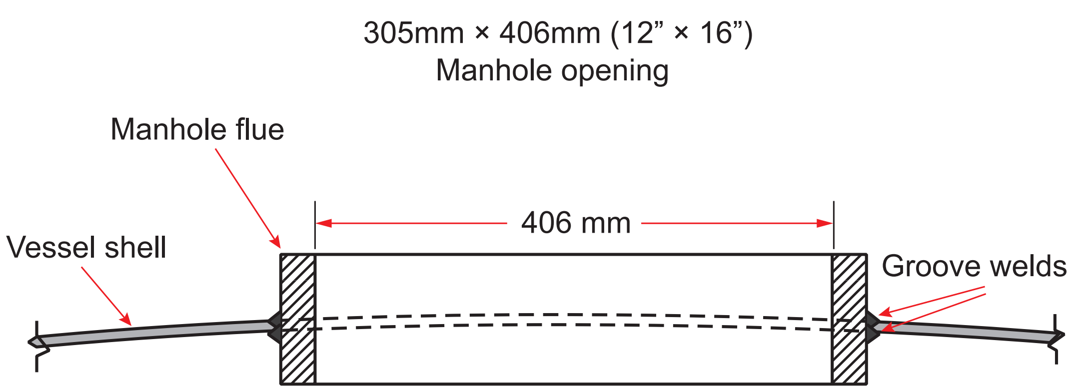
Figure 22 – Acceptable Firetube to Tubesheet Attachment



In order to carry out inspection, cleaning, and repair, it is necessary to provide access to various parts of boilers. Manholes allow human entry into drums and shells. Handholes give access to smaller parts, such as headers and waterlegs. A cover plate and gasket seal the opening when the boiler is in service, and a yoke holds the cover plate in place.

Figure 23 shows a cross-sectional view of a manhole flue, attached to a shell with full penetration groove welds that extend around the circumference of the flue. Note that in this circumstance, the attachment is double-welded. The ASME permits single-welded attachments, with some exceptions. The single-welds must be the equivalent of a double welded butt joint, by providing means for accomplishing complete penetration.

Figure 23 – Manhole Flue (Reinforcing Ring) Attachment



The manhole flue serves two important purposes. It provides a flat surface for the manhole cover plate to seal against, and it reinforces the shell where the manhole opening is.

Figure 24 shows a 300 mm by 400 mm flued-in manhole, in an air receiver. A cover plate with gasket seals the opening in the vessel. Yokes hold the cover plate in place.

In the case of the vessel shown in Figure 24, the manhole flue provided insufficient **reinforcement** strength for such a large opening. Therefore, a repad (short for "reinforcing pad") stiffens the area of the shell weakened by the hole. Note the following:

a) The repad is welded to the shell with a fillet weld around the circumference of the repad.
b) The manhole flue is welded to the repad with a fillet weld around the circumference of the flue.
c) There is a small hole deliberately drilled in the repad. This "tell-tale" hole will show if the pressure vessel weakens and fails beneath the repad.

Refer back to Figure 14 for more details regarding repad attachment.

Figure 24 – Flued in Manhole with Reinforcement Pad

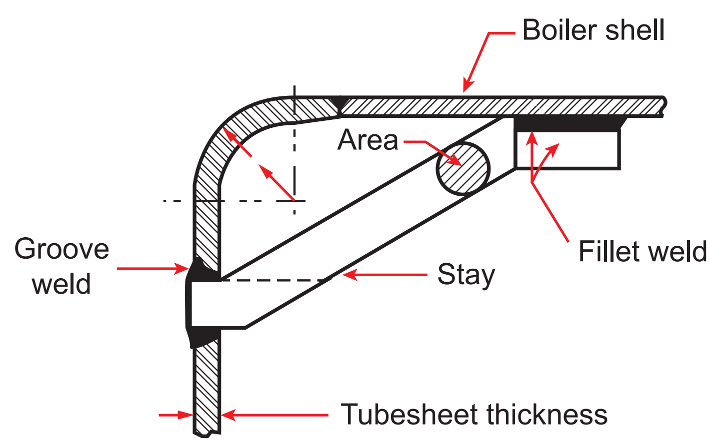
Other components are strength-welded to the pressure boundary of the vessel. Certified pressure welders must perform these welds. They include:

- Stays and staybolts (Figure 25 and Figure 26)
- Feedwater, continuous blowdown, and chemical feed line brackets
- Lifting lugs (Figure 27)

Stays and staybolts are necessary to prevent flat boiler or pressure vessel surfaces from bulging due to the effects of pressure. Stays tie flat surfaces to other supporting structures, thereby carrying the bulging force. The weld attachments must be strong enough to carry the tensile load acting on the weld deposits.

Figure 25 shows a diagonal stay, which ties a flat tubesheet to a boiler shell. Notice the head attachment is by groove welds, and the shell attachment is by fillet welds. It is unacceptable to make the shell attachment of a diagonal stay using anything other than a fillet weld. Diagonal stays are installed in the steam space of firetube boilers, because they do not obstruct the manhole openings. Through stays, if used instead of diagonal stays, would travel directly under the manhole opening, interfering with waterside access.

Figure 25 – Diagonal Stay Attachment



If additional support is required for the water-wetted tubesheet surfaces of a firetube boiler, they are often supported by longitudinal or "through" stays. These through stays are long rods that extend from the rear tubesheet to the front tubesheet. The stays are usually fastened to the tubesheets by welding (Figure 26).

Figure 26 shows the method of supporting the flat surfaces of a boiler waterleg using staybolts. Staybolts are very short through stays that support flat surfaces in close proximity to one another. Waterlegs are commonly found in firebox boilers and locomotive boilers, adjacent to the furnace.

Figure 26 – Through Stay and Staybolt Attachment / Waterleg Construction

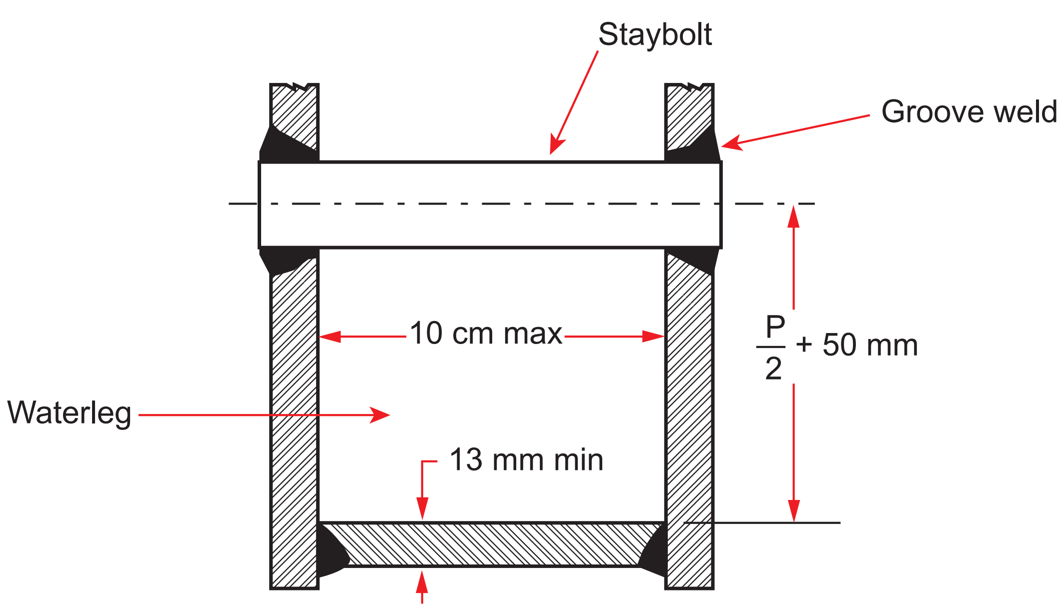
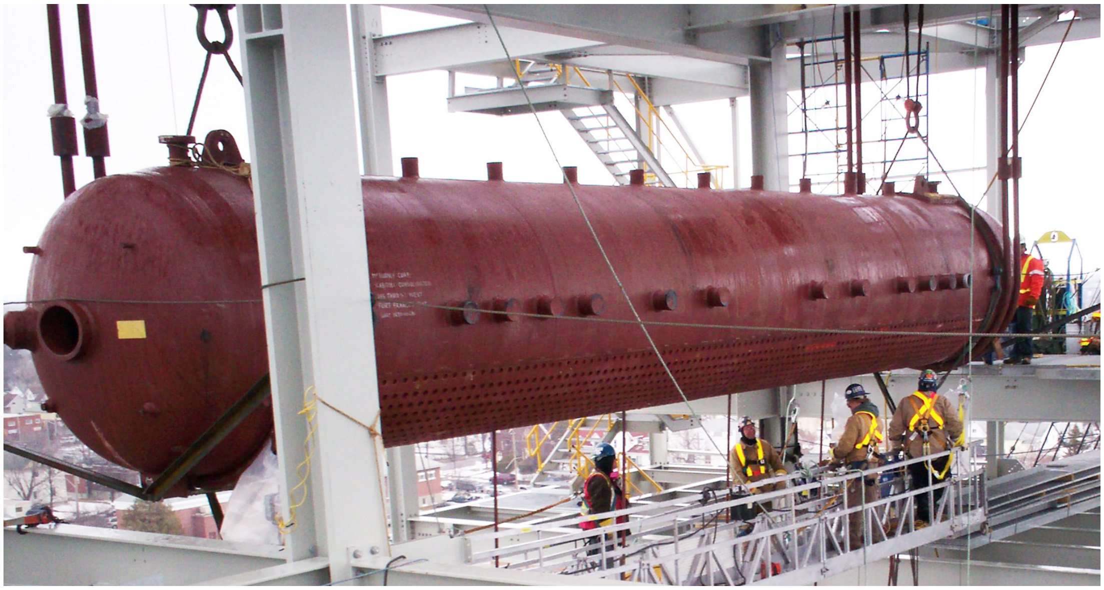


Figure 27 shows a steam drum during field erection. Notice the row of steam outlet tube stubs at the top of the drum, and riser tube stubs on the side of the drum. At each end of the drum, at the top surface, are welded nozzles with flanged terminations for mounting safety valves. Other welded attachments shown are lifting lugs on the top of the shell, and a manhole flue in the front head. Prior to erection, the entire assembly would have been post-weld heat treated in an oven.

Figure 27 – Steam Drum Being Field Erected



Pressure Boundary Seal Welds

A seal weld differs from a strength weld in that it is not designed to have the same strength. A seal weld's only purpose is to prevent leakage.

Welds are sometimes used to seal up the following assemblies.

- Expanded watertube-to-shell attachments (Figure 28)
- Expanded firetube-to-shell attachments (Figure 28)
- Handhole openings of very high pressure boilers (Figures 29 and 30)
- Membrane walls ligaments. (Figure 31)

Note that the components are first assembled in the conventional method, without welding. The weld beads are applied after assembly.

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Figure 28 shows ASME code acceptable seal welds applied to expanded tube attachments. The left-hand side image shows a seal-welded firetube, and the right-hand side image shows a seal-welded watertube. The tubes must be first expanded into place, because these welds are not designed to be strong enough to handle the entire force exerted by the boiler's internal pressure.

Figure 28 – Seal Welded Tube Ends

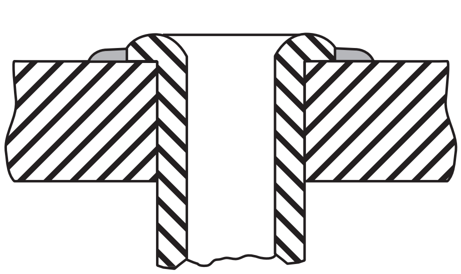


Figure 29 shows a cross-sectional view of a handhole seal-welded into place. The seal occurs where the handhole mates with the boiler shell. The high pressure of the boiler forces the handhole tight against the mating surface. The weld bead extends around the circumference of the handhole, to help prevent leakage. If maintenance is required, the weld bead must be ground away or carbon-arc gouged before removing the handhole.

Figure 30 shows two welded handholes installed in an upper header of a utility boiler. Note the thickness of the insulation surrounding the handholes, and that the header is top-supported.

Figure 29 – Seal Welded Handhole

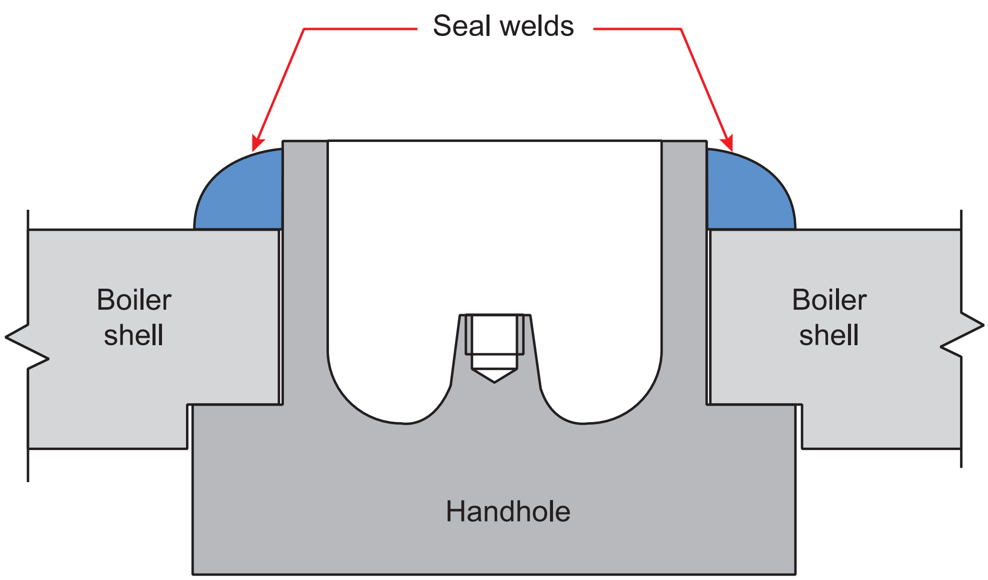
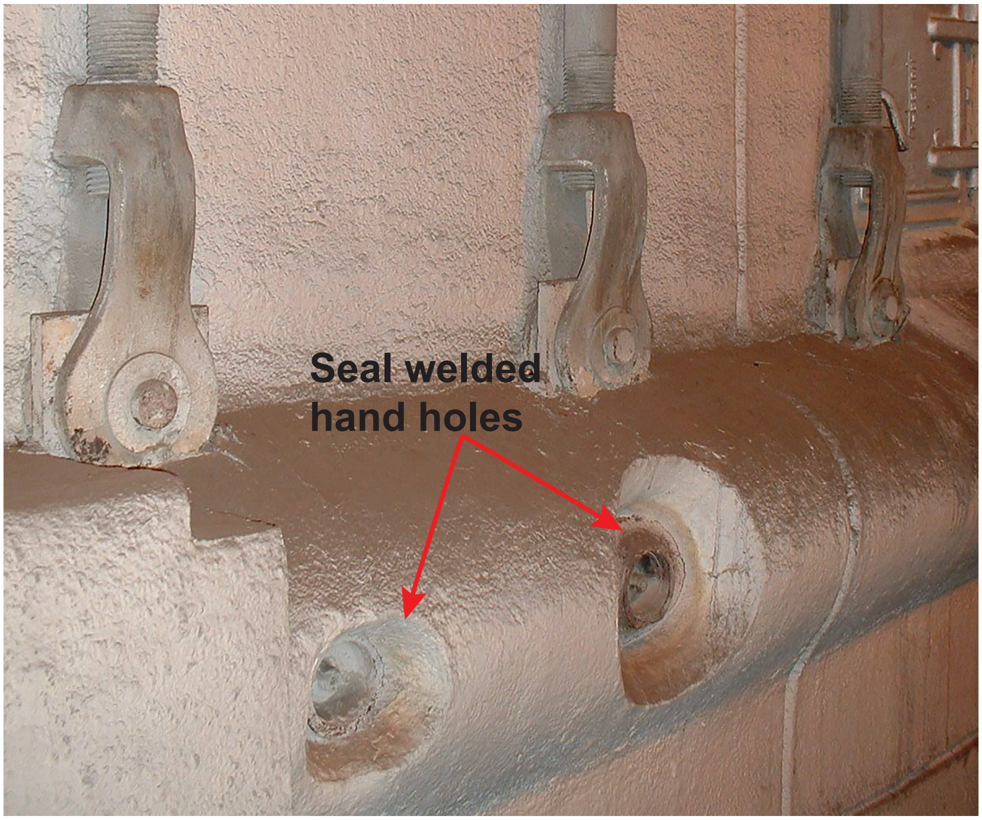
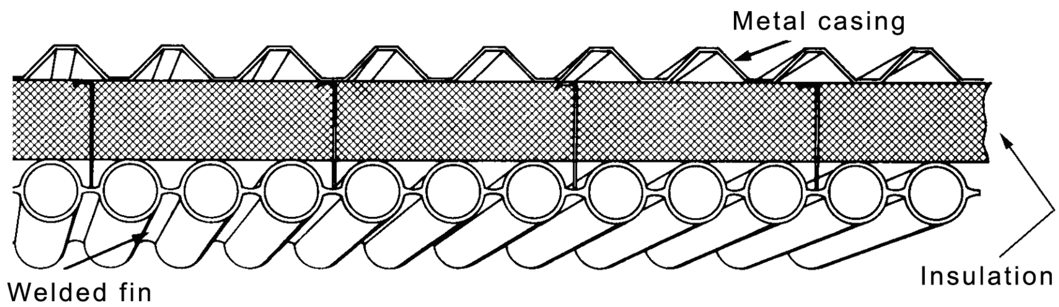


Figure 30 – Seal Welded Handhole in a Header



The welded fin tube waterwall panels in Figure 31 illustrate a different application of pressure boundary seal welds. This weld does not prevent water or steam leakage; rather, it prevents flue gas, ash, and soot leakage from a pressurized furnace into a boiler room. These welds are factory-performed by welder operators using fully automatic welding machinery. After welding the tubes to the membranes, the waterwall panel is bent to the proper shape for installation.

Figure 31 – Welded Fin Tubes (Membrane Walls)



(a)

(b)

(Courtesy of Combustion Engineering)

Chapter Summary

Welding is a highly technical field, requiring knowledgeable design engineers and skilled welders. The **ASME Code Section IX** helps engineers design sound weld joints and procedures. It provides:

- A wide range of weld joint designs (groove, fillet, tee, etc.)
- Welding processes (SMAW, GMAW, etc.)
- Parent metal and filler metal chemical composition (carbon or alloy steels)
- Weld position

ASME IX also instructs manufacturers on how to qualify their welders. When all these variables are controlled, the resulting welded vessel will be strong and safe over its useful life.

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CHAPTER 3

Boiler and Pressure Vessel Weld Inspection

Learning Outcome

When you complete this chapter you should be able to:

Describe inspection processes and testing methods for welds and materials.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Describe common weld defects.*
2. *Describe the process of Visual Testing of welds.*
3. *Describe the process of Penetrant Testing for detecting weld or material defects.*
4. *Describe the process of radiographic weld testing.*
5. *Describe the process of ultrasonic weld testing.*

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CHAPTER INTRODUCTION

Welding was already used for shipbuilding in 1914, when the first edition of the **ASME Boiler and Pressure Vessel Code** was being prepared. However, welding was considered unreliable, and was not permitted by the first edition of this code. In 1918, the ASME finally permitted welding, but only on boiler parts that did not rely on weld strength for vessel integrity.

Over the years, welding has become the preferred method of boiler, pressure vessel, and pressure piping construction. This would not have happened except for two factors, which led to welding's reputation as a reliable construction method.

1. Improved welding processes, such as SMAW, GMAW, and GTAW
2. Improved methods of detecting, evaluating, and repairing weld imperfections

If weld inspection technology had not kept pace with welding process technology, industry would have likely remained skeptical about the reliability and safety of welds. Welding process adoption would have proceeded much slower than it did. Inspection, then, proves the reliability and safety of a welded structure, and is a critical part of boiler and pressure vessel manufacturing.

This chapter examines weld imperfections and defects. It also looks at the techniques boiler and pressure vessel inspectors use to prove that welded vessels are safe.

OBJECTIVE 1

Describe common weld defects.

WELD DEFECTS

Power Engineers will meet welding inspectors in the power plants where they work, or on construction sites. The welding inspector may represent one of the following:

- Manufacturer
- Purchaser
- Insurance company
- Government agency, such as the jurisdictional safety/boiler Inspector

The inspector's job is to determine if welds made during construction or repair are sound or defective.

To identify a weld as "defective," three elements must be met.

1. The condition must be observed.
2. The observed condition must be compared to an acceptance standard.
3. A judgement must be made.

An observed condition is called an "**indication**." Indications in welds may be bubbles, foreign matter, or cracks. Some indications may be dimensional (warped or misaligned metal parts, or misshaped weld deposits).

Inspectors perform many kinds of non-destructive tests. These help to find out information about these indications, such as:

- Length
- Width
- Depth
- Position
- Orientation

To properly identify and locate the indication, the first step is for the inspector to perform **non-destructive examination (NDE)**.

For boilers and pressure vessels, the procedures for conducting non destructive examination are found in **ASME Code Section V: Nondestructive Examination**. Careful observation, using non-destructive testing, is necessary before the next step.

Next, the indication is compared to standards to see if it is acceptable or rejectable. Small indications, or larger indications found in non-critical locations, may be perfectly acceptable.

Large indications, or small indications in critical locations, may be unacceptable. **ASME I Power Boilers** contains the acceptance criteria for NDE, conducted according to **ASME V**, **on Power Boilers (Non-Mandatory Appendix A-250)**.

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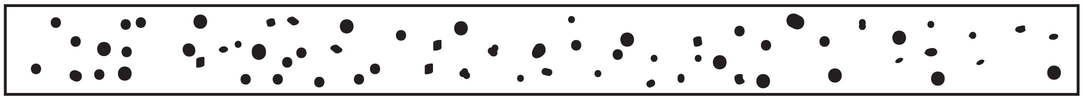
Figure 1 – Acceptance Criteria for Rounded Indications (from ASME I A-250)



General note: Typical concentration and size permited in any 6 in. (150 mm) length of weld

Acceptance standards may differ in various construction codes. An indication that is acceptable in **ASME I Power Boilers** may be unacceptable in **ASME III Nuclear Construction**, due to the criticality of weld integrity in nuclear applications. The acceptance standards guide the inspector to properly evaluate the indication.

Finally, the inspector makes a judgement. If the indication is unacceptable according to the acceptance criteria, the indication is then called a "**defect**" and must be repaired. Acceptable indications are never called "defects." If an indication is found acceptable, it is referred to as a "**flaw**."

Types of Weld Defects

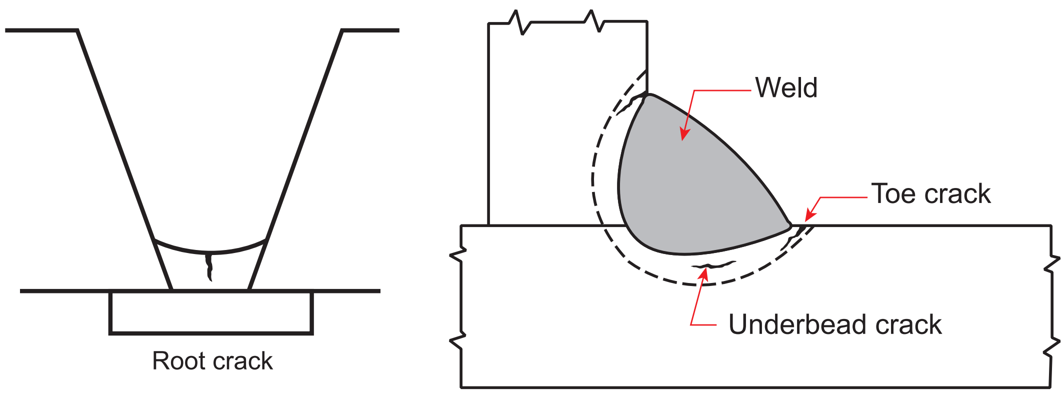
ASME V lists many forms of weld defects. These include:

- Cracks
- **Porosity**
- **Inclusions**
- **Incomplete fusion**
- **Undercut**
- **Incomplete penetration**
- Dimensional

Cracks

Cracks may occur at the face, root, or toe of the weld. Cracks may be sub-surface or extend to the surface of the material. A crack that extends to the material surface will grow, and lead to eventual failure of the material.

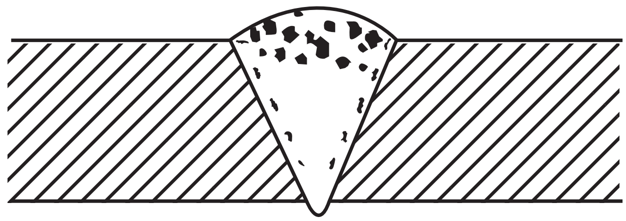
Figure 2 – Weld Joint Crack Locations



Porosity

Porosity is caused by gas bubbles trapped in the solidifying weld metal. It may be sporadic or found in clusters. Some sporadic porosity is usually acceptable. Cluster porosity is generally unacceptable and requires repair.

Figure 3 – Cluster Porosity



Inclusions

Inclusions are pieces of slag or tungsten that are trapped in the weld deposit. Slag inclusions occur because the weld surface was not adequately cleaned between passes. Tungsten inclusions occur from improper GTAW welding technique.

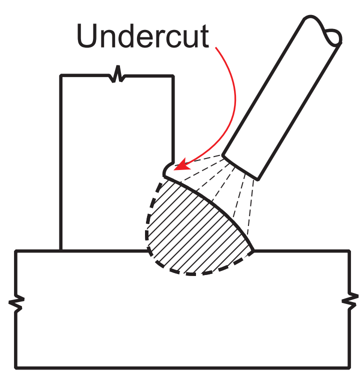
Incomplete Fusion

Incomplete fusion results when the weld metal does not penetrate and combine with the parent metal. This has the same weakening effect on the material as a crack.

Undercut

Undercut is a groove melted into the parent metal at the toe of the weld, and left unfilled by weld metal. It reduces the thickness of the parent metal, weakening it.

Figure 4 – Undercut



Incomplete penetration

Incomplete penetration refers to when filler metal does not extend through the entire thickness of the parent metal, to the opposite side of the weld joint. When this occurs, the weld metal is not as thick as the parent metal, and the weld joint is therefore weak.

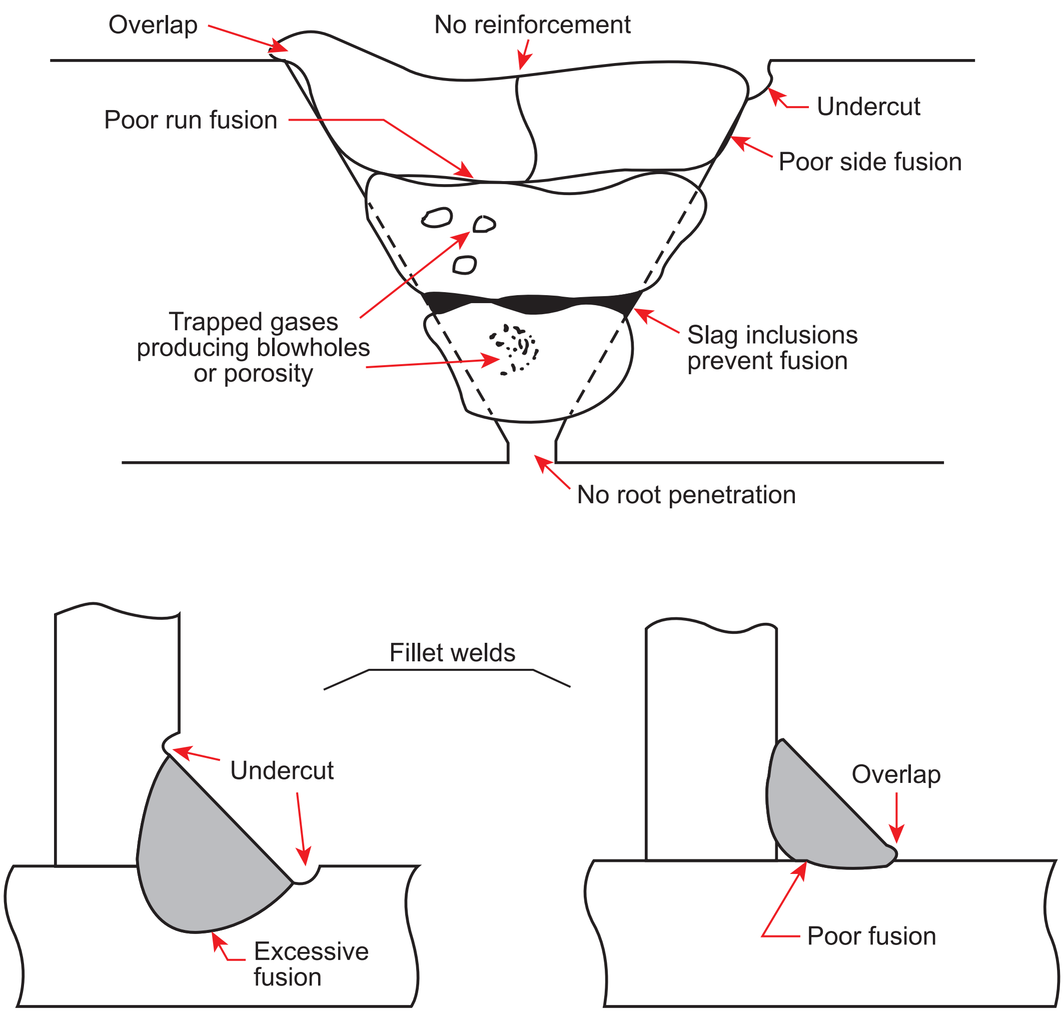
Dimensional defects

Dimensional defects may include warpage, misalignment, and weld profile defects. These may include any of the following:

- Excessive **concavity**
- Excessive **convexity**
- Excessive or inadequate **reinforcement**
- **Overlap**

Figure 5 shows many of these potential weld defects.

Figure 5 – Weld Defects



These defects are also known as "discontinuities." "**Discontinuity**" means "not continuous". In other words, where a crack, or undercut, or an inclusion occurs, the metal is not continuous. It is interrupted by either a void or a piece of foreign matter.

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Objective 2

Describe the process of Visual Testing of welds.

Non-Destructive Methods for Testing Welds

Inspectors employ various methods of non-destructive examination. **ASME V** lists many NDE techniques, and describes how to perform these tests properly.

- **Radiographic testing (RT)**
- **Ultrasonic testing (UT)**
- **Magnetic Particle testing (MT)**
- **Liquid Penetrant testing (PT)**
- **Visual testing (VT)**
- Leak Testing (LT)
- **Electromagnetic (Eddy Current) testing (ET)**
- **Acoustic Emission testing (AE)**

It is most important for the fourth class Power Engineer to be aware of the following testing.

- Visual testing
- Penetrant testing
- Radiographic testing
- Ultrasonic testing

Visual Testing (VT)

Visual testing (VT) is of great importance. It constitutes the principal basis of acceptance for many types of weldments. It is the most widespread method of inspection because it is easy to apply, quick, and relatively inexpensive. It gives very important information with regard to the welds and whether they conform to specifications.

VT usually begins prior to fabrication. It includes:

- Reviewing drawings and specifications
- Checking weld procedures
- Selecting proper materials

Defects in the parent material, such as **laminations**, seams, or scale, may be detected prior to construction.

After the parts are tacked together for welding, the inspector can identify:

- Incorrect root openings
- Improper joint preparation and alignment
- Other features that may affect the quality of the finished weld joint

VT is also used to check details of the work while welding is in progress. **Weld consumables** such as electrodes and shielding gas, current settings, and welder qualifications can be monitored during production.

Work can and must be stopped at any point in production if a condition exists that may impact the final weld quality. For example, it is very common to inspect tack welds for cracking prior to permitting a root pass to proceed. It is also common to inspect a root pass before permitting subsequent passes. Defective tack or root welds require work stoppage, weld removal, and re-welding.

To complete the visual inspection cycle, inspection before and during welding must be followed by post-weld inspection. VT can be readily applied at all stages of production. It has no equal in detecting defects while they are still easy to correct.

Tools for Visual Testing of Welds

The inspector conducting visual testing relies primarily on a flashlight and a magnifying glass. The flashlight is shone parallel to the material surface in order to reveal surface features. As well, various gauges and instruments are used to find dimensional defects. These tools measure:

- **Weld leg** length
- **Weld throat** thickness
- Concavity
- Convexity
- Reinforcement depth

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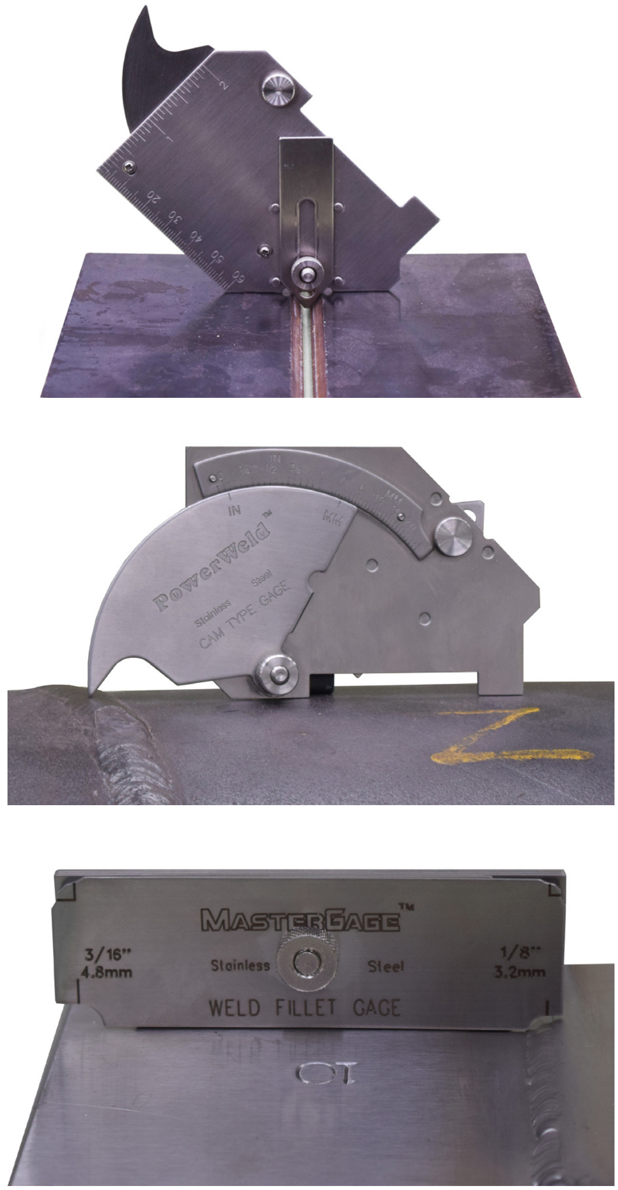
Some of these gauges are shown in Figure 6.

Figure 6 – Gauges for Visual Testing of Welds



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Objective 3

Describe the process of Penetrant Testing for detecting weld or material defects.

Liquid Penetrant Testing (PT)

Liquid penetrant testing (PT) involves applying a highly visible liquid to highlight surface indications, thereby assisting visual testing. The liquid penetrates into and highlights any indications that are open to the surface.

PT uses penetrating fluids that are either highly visible under white light, or are highly visible under **black (ultraviolet) light**. These two types of **penetrants** are:

1. **Colour Contrast Penetrant** ("Visible Dye" Penetrant)
2. **Fluorescent Liquid Penetrant**

PT effectively detects cracks, seams, laminations, and porosity. Part of its usefulness lies in the fact that it detects features open to the material surface, which is always a concern to the inspector. Cracks that extend to the surface are locations where stress concentrates, and failure begins.

PT is only effective on materials that are non-porous and smooth. For example, a crack extending to the surface of a mild steel bracket could be readily detected using PT. However, a crack in a cast iron casting would likely be obscured because the penetrant would flow into every part of the rough surface, giving **false indications**.

PT, in either its visible or fluorescent form, can be used for locating defects that extend from one side of a material to the other side. Such a condition, if it existed in a boiler or vessel, would result in leakage.

To detect defects that extend through the entire thickness of the material, penetrant is applied to one side of the material being examined, and **developer** is applied to the opposite side. If porosity or cracks extend through the material, the developer will draw the penetrant through the defects to reveal the flaw. In other words, the penetrant will show up on the side opposite to that on which it was originally applied.

Colour Contrast (Visible Dye) Penetrant

Visible dye penetrant inspection is the most simple penetrant method. It requires the least equipment, and relatively less technical training than other methods of NDE. Visible dye penetrant shows surface discontinuities as bright red lines or dots on a white background. Red is the preferred dye colour, because it contrasts well on a white background. Visible dye penetrant testing does not require much equipment (cans of solvent, penetrant, and developer). The equipment costs are minimal, and little skill is required to become proficient at the test. Therefore, many power engineers employ this NDE method in their workplace.

Briefly, the process consists of the following steps.

1. The surface to be inspected is thoroughly cleaned with a penetrant-compatible solvent.
2. A red dye penetrant liquid, with low viscosity and exceptional surface-wetting ability, is applied to the surface by brushing, spraying, or dipping.
3. An interval of five to ten minutes ("**dwell time**") permits the penetrant to soak into surface discontinuities, via capillary action.

4. At the end of the dwell time, the excess penetrant is removed from the surface by washing with the solvent, followed immediately by a thorough water rinse.

5. The surface is then dried and a developer compound is applied in a fine, even spray. The developer is like a white talcum powder. It serves as a "blotter" and as a contrasting white background that highlights the red dye.

6. The developer will then absorb the red penetrant from any hidden surface indications. It reveals flaws by the "**bleedout**" of the red dye against the white background of the developer. The length of the bleed roughly indicates the length of the discontinuity. The width of the bleed roughly indicates the depth of the discontinuity.

Figure 7 illustrates these steps.

Figure 7 – Visible Dye Penetrant Steps

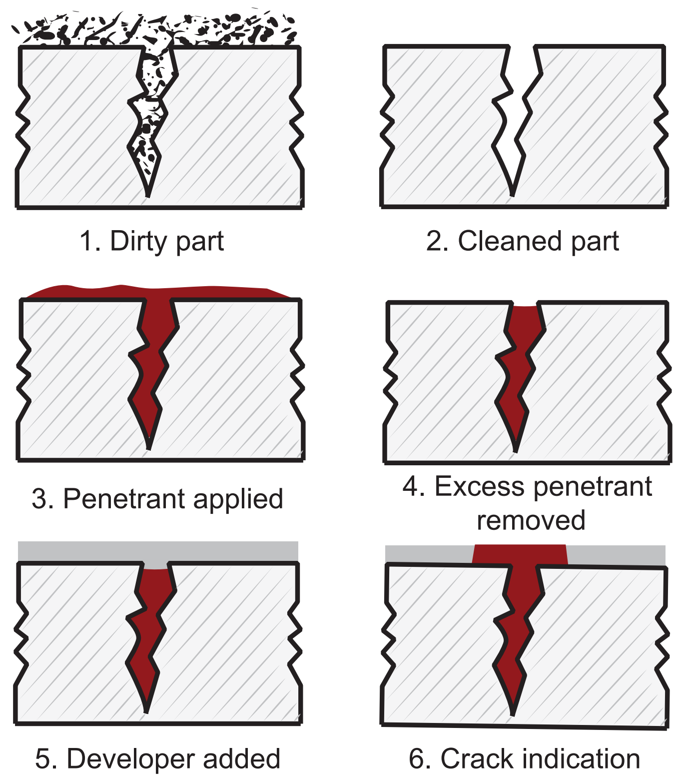
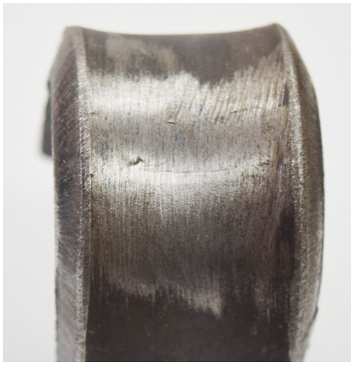


Figure 8 – Visible Dye Penetrant Indication on a Weld Test Coupon

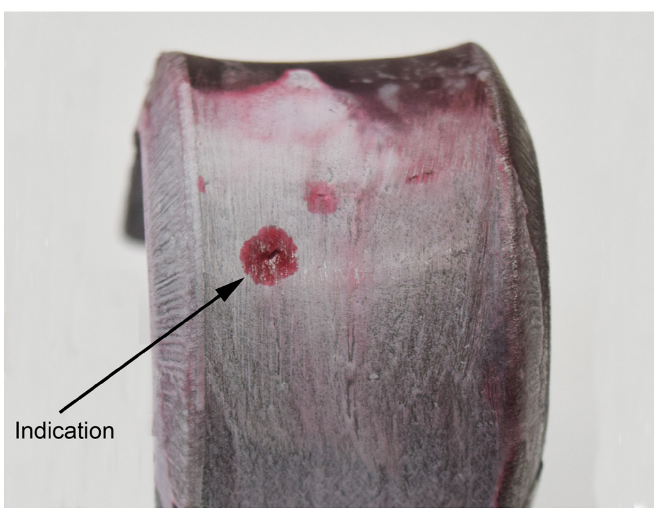


1. Cleaned, ready for dye penetrant

2. Dye penetrant applied

3. Excess dye removed

4. Developer applied



5. Fully developed

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Fluorescent Penetrant

The fluorescent penetrant testing procedure is essentially the same as the dye penetrant test procedure, except that the bled-out penetrant is observed under "black" (ultraviolet) light. **Fluorescent** materials emit visible light when exposed to ultraviolet light. The fluorescent penetrant glows green, which is a colour to which the human eye is naturally sensitive.

In addition to the normal detection of cracks and leaks, fluorescent PT is particularly suited to revealing micro cracks in welds.

CAUTION

Fumes produced by many PT (Penetrant Testing) chemicals may be hazardous. Use in well-ventilated areas. Follow product manufacturer PPE recommendations.

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Objective 4

Describe the process of radiographic weld testing.

Radiographic Inspection

Radiography (RT) is a highly valued nondestructive test method that shows defects in the interior of welds that would otherwise go undetected. Because it examines the material surfaces and its interior composition at the same time, the ASME refers to RT as a type of "**volumetric examination.**"

Radiation Sources

Short wavelength electromagnetic radiation has two important properties, that allow it to be used for finding discontinuities and defects in material, even if the defect is below the surface:

a) Radiation can penetrate objects that light cannot pass through.

b) Radiation can expose photographic film.

Short wavelength electromagnetic radiation may come from x-ray tubes or radioactive elements. **X-ray** equipment uses x-ray tubes that operate on the same principle as the x-ray machines found in medical laboratories. Industrial x-ray machines are far more powerful than those used in medical service.

The radioactive elements radium and cobalt can also be used as radiation sources. As these elements decompose, they emit **gamma rays** capable of penetrating metal and exposing film. RT equipment using gamma ray sources are portable and require no external power source. They are ideally suited for use in the field or on construction projects. X-ray machines, too, are becoming smaller and more portable by using internal battery power.

CAUTION

Ionizing Radiation is a type of electromagnetic energy that travels in the form of waves (gamma or X-rays). It has the ability to displace electrons from atoms. Exposure to ionizing radiation can cause severe burns, sterility, cancer, and death, depending on the duration and severity of exposure.

Radiographic Testing Procedure

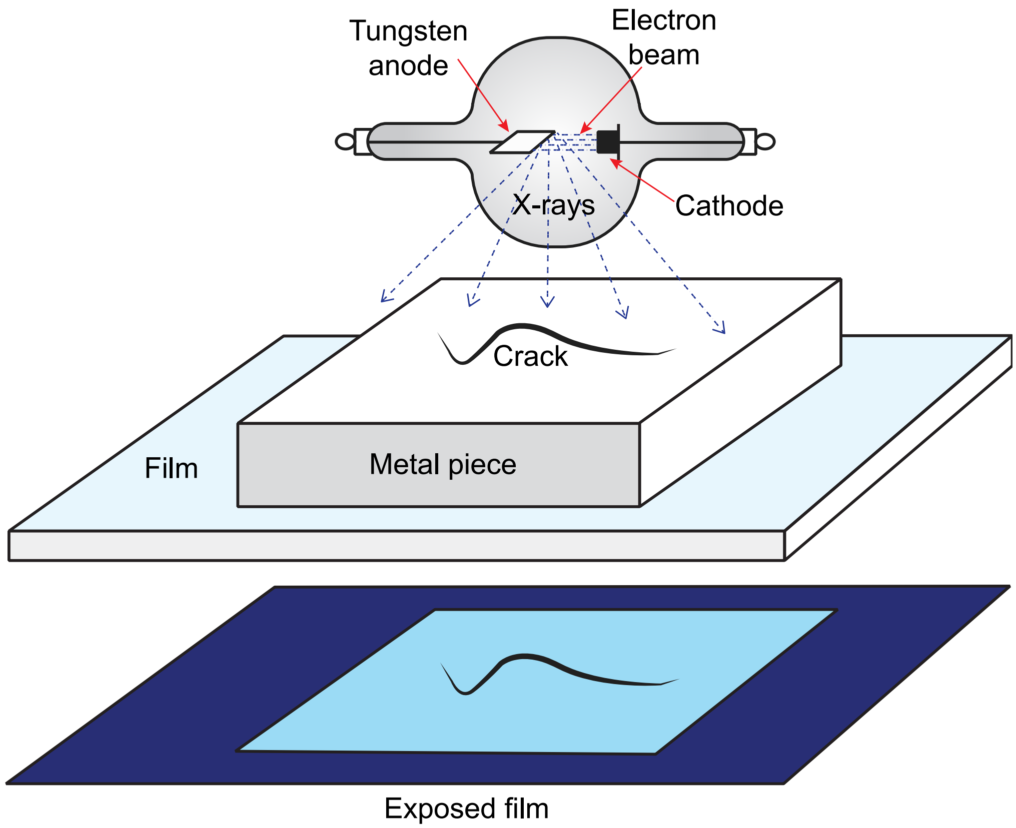
To begin a radiographic test, a radiation source is placed on one side of a weld joint, and a photographic film is placed on the other side. When the radiation is released, it passes through the weld joint and exposes the film. The time of the exposure is carefully controlled to properly expose the film. An overexposed film will be dark and featureless, and an underexposed film will be bright and featureless.

The radiation is absorbed by the metal to lesser or greater degrees, depending on the thickness and the type of metal. Cracks, porosity, and slag inclusions affect the amount of radiation absorbed, causing variations in the film exposure.

Consider a crack in a weld, for example. Cracks are essentially places where no metal is present. A crack, then, cannot absorb radiation. However, the metal surrounding the crack does absorb radiation. The photographic film, then, becomes more highly exposed in the location of the crack. As a result, the crack appears as a dark line on the film, contrasted by the surrounding lighter colour that represents the surrounding parent metal.

Figure 9 shows the RT process, and the resulting film exposure. Note that the crack appears dark on the film.

Figure 9 – Radiographic Test Image



To control and document the quality of an RT test, strips of metal called **penetrameters** (or "pennies") are used during the radiographic inspection of a weld. Penetrameters are made of the same materials as the welded parts. Usually, several small holes are drilled in the penetrameter, which is then placed adjacent to the weld. When the radiographic "picture" of the weld is taken, the outline of the penetrameter will be visible on the film.

Side Track

The proper name for a penetrameter is **Image Quality Indicator (IQI)**.

The clarity of the penetrameter's film image indicates the sensitivity, exposure, and clarity of the radiograph. Figure 10 shows a style of penetrameter designed to meet the requirements of **ASME V**. Other penetrameters are made of several wires of various thicknesses, attached to a common frame. The clarity of the wire images on film indicates the quality of the radiographic image.

Figure 10 – Hole-Style Penetrameter, according to ASME V

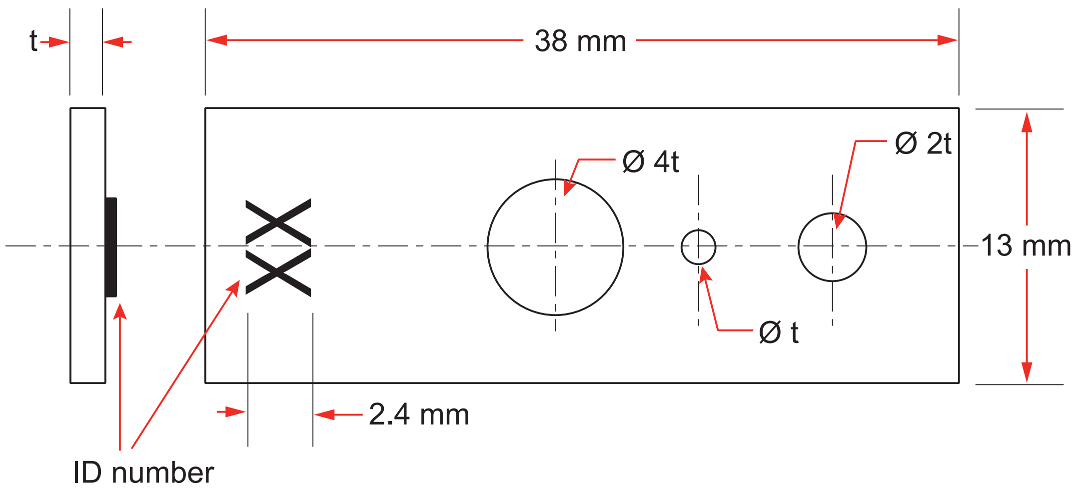
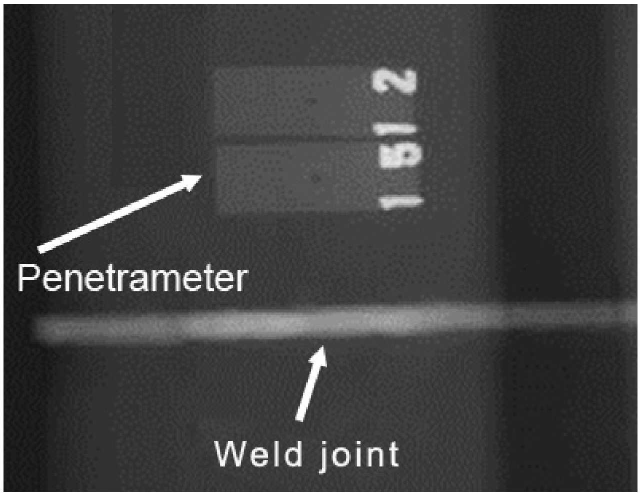


Figure 11 shows how penetrameters appear on a radiographic film. The ID numbers appear brightest because the numbers are made of lead, which is an effective radiation shield.

Figure 11 – Hole-Style Penetrameters Shown on a Radiographic Image of a Weld Joint



Though reliable and highly effective, radiographic testing is also technically complex and expensive. Industrial x-ray equipment costs up to tens of thousands of dollars. Technicians must be highly trained and qualified experts. Also, some indications (such as laminations) are difficult or impossible to detect, because of their orientation in relationship to the film and radiation source.

CAUTION

RT is commonplace in functioning power plants, and may be performed while Power Engineers and other employees are present. The location undergoing RT must be roped off. Access to the segregated area must be limited only to the NDE technicians performing the tests. All plant personnel must be advised when the RT begins and when it is safe to re-enter the area.

Objective 5

Describe the process of ultrasonic weld testing.

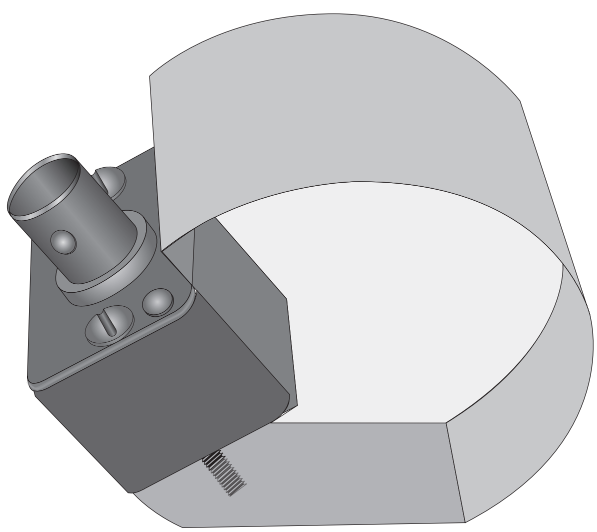
Ultrasonic Inspection

Ultrasonic Inspection (UT) is another volumetric NDE technique. **Ultrasound** is high-frequency sound that cannot be detected by the human ear. Sound waves travel through matter, regardless of whether it is gaseous, liquid, or solid. Sound also reflects ("echoes") from surfaces when the sound reaches a material that conducts sound differently. Using these principles, ultrasound of various frequencies can be used to find internal discontinuities in solid materials. The discontinuities may be cracks, lamination, inclusions, or porosity. When sound which is travelling through solid metal reaches a void (such as a crack), a reflection is produced that can be detected by a sensitive **transducer**.

Figure 12 shows an ultrasonic transducer used for weld inspection. A cable attaches an **oscilloscope** to the transducer port. The transducer itself is mounted to a 45° angle Plexiglas block, in order to introduce the ultrasound into the metal specimen at an angle. A special fluid, known as a "**couplant**," is placed between the angle block and the metal specimen to permit the ultrasound to exit the transducer and enter the specimen.

The transducer uses the **piezoelectric effect** to vibrate a quartz wafer, creating pulses of ultra high frequency sound. The transducer also responds to the ultrasound reflections. It converts the ultrasound energy to an electrical pulse, which an attached oscilloscope interprets and displays as a spike.

Figure 12 – Ultrasonic Transducer Mounted on an Angle Block



The location of the echo source can be mapped on the surface of the material. The time that it takes for the sound to reflect back is measured and used to determine the depth of the indication. The sound frequency can be adjusted to be sensitive to discontinuities that are either fine or coarse. High frequency vibrations are more sensitive to fine discontinuities than lower frequency ultrasound. However, higher frequency ultrasound will generate more "noise," that may mask the location of an indication.

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Ultrasonic testing is commonly used to determine material thicknesses. When only one side of the vessel material is available for inspection, small, portable and relatively inexpensive hand-held units are used to determine vessel wall thicknesses for in service equipment.

Figure 13 shows a portable ultrasonic thickness tester, and a small transducer about the size of a human fingertip. The portable units may have built-in calibration blocks for tuning the equipment before use. The one shown has the ability to check the thickness of a variety of metals. Less expensive testers may be designed to only measure mild steel. A screen reads the thickness of the material directly.

Figure 13 – Portable Ultrasonic Thickness Tester and Transducer

For weld testing, the instantaneous sound-wave signal is displayed on an oscilloscope screen. As the NDE technician guides a hand-held transducer over the material surface, the screen shows points of unusual sound reflection, as "peaks". These peaks identify the location and depth of sub-surface discontinuities. The technician documents the location, size, and type of discontinuity, (crack, porosity, inclusion, etc.) so that repairs can be made.

UT is volumetric inspection. There are situations where **ASME I** code allows UT to substitute for RT. **ASME I**, **Table PW-11** outlines the required volumetric examination of welded boiler butt joints during construction.

Ultrasonic inspection may be used to detect flaws in all types of welded joints such as nozzles, manholes, and tube plates to shell. Ultrasonic inspections may be carried out on boilers, pressure vessels, and piping systems that are in service during the inspection. Technicians are highly trained, and the equipment used is expensive, though not as costly as RT equipment.

Chapter Summary

There is no such thing as a perfect weld. Manufacturers hope that modern welding processes and procedures, combined with skilled welders, will result in vessels that are safe and durable. NDE supports the manufacturers' claim that the boiler welds are safe for the conditions they will encounter.

Of the four NDE methods discussed, it is important to understand that no single method is, overall, better than another. Certain NDE methods are better at finding specific kinds of defects than others; however, each method has its own strength.

ASME V guides weld inspectors in choosing the proper NDE method for discovering particular kinds of defects. Often two or more NDE techniques are used on the same material specimen to reduce the chances a defect will be overlooked. More NDE methods, and more detail on the methods covered here, are discussed in further chapters.

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UNIT SUMMARY

In summary, this unit helps Power Engineers to operate, inspect, maintain, and repair power plant equipment safely. It has provided practical knowledge of material properties, construction methods, and inspection methods.

A self-assessment tool is available on MyPower LMS. Login using the unique user ID and password found on the inside front cover of Unit 1.

Notes

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UNIT A-6

Knowledge Exercises and Unit Glossary

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Knowledge Exercises – Chapter 1

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. List the mechanical properties of materials and provide a brief description of each.

2. Describe a Brinell Tester. Explain its purpose and how it operates.

Chapter 1 (Cont.)

Objective 2

3. Briefly describe the ferrous metal making process.

4. List some of the most important elements added to steel to produce alloy steel and give a description of their effect on the properties of the steel.

Objective 3

5. List the types of non-ferrous materials commonly used in power plants and give a brief description of each.

Knowledge Exercises – Chapter 2

Name: ______________________ Date: ______________________

Instructor: ______________________ Course: ______________________

Introduction

1. What ASME Code is concerned with welding of boilers and pressure vessels?

2. In your own words, define welding.

Objective 1

3. How are soldering and brazing similar, and how are they different?

Objective 2

4. What is the most common fuel gas used in OFW? What are the hazards associated with using this gas?

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Chapter 2 (Cont.)

5. How does an oxy-fuel torch cut through steel? What common metal cannot be cut with this torch?

Objective 3

6. How is SMAW straight polarity different from reverse polarity?

7. A CSA W48 electrode is designated "E4918." What is the equivalent AWS electrode? What weld position is it suitable for?

8. What is the purpose of shielding gas? What processes use shielding gas? What common gases are used for shielding?

Chapter 2 (Cont.)

Objective 4

9. What does HAZ stand for? How is a HAZ formed? Why is a HAZ a problem?

10. Name two ways of eliminating a HAZ.

Objective 5

11. Name the two main categories of weld joints.

12. What joint preparation is needed to weld very thick boiler metal?

13. Define:

    a) Depth of fusion

    b) Root pass

    c) Penetration

    d) Weld face

Chapter 2 (Cont.)

e) Tack weld

f) Toe

g) Reinforcement

Objective 6

14. Who is qualified to weld on a boiler or a pressure vessel?

15. Circle the correct answers. Stays are welded in place using (strength/seal) welds. Welded handholes use (strength/seal) welds.

Knowledge Exercises – Chapter 3

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. When is an indication called a "defect?"

2. Define the following terms:

   a) Porosity

   b) Inclusion

   c) Undercut

   d) Overlap

   e) Discontinuity

Objective 2

3. Fill in the blanks below, using the symbols for the NDE techniques discussed in this chapter. More than one technique can be used.

   Least expensive NDE method ____________

   Requires the least equipment ____________

   Requires the most expensive equipment ____________

   A method Power Engineers may use in the powerhouse ____________

   Requires the most inspector training and skill ____________

Chapter 3 (Cont.)

Objecitve 3

4. List the steps to follow when performing a Liquid Penetrant test.

Objective 4

5. You are an operator on shift, and you are informed that radiographic testing will be taking place in your plant.

   a) What hazards are associated with radiographic testing?

   b) What precautions should you take to ensure your safety and the safety of others in the plant?

Objective 5

6. An oscilloscope being used for UT shows a peak from a reflected sound wave. List five things inside the specimen being tested that may have caused this reflection.

Unit A-6 Glossary

Term	Definition
Acetylene	A highly unstable fuel gas with the chemical formula C_2H_2, used for welding, brazing, and flame cutting processes.
Acoustic emission Testing (AE)	An NDE method that utilizes a class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material.
Alloy	A solid solution of a metal containing two or more metals or non-metals.
Alloy steel	A solution of steel with significant quantities of other metallic elements, designed to improve specific mechanical or chemical properties of the steel.
American society of mechanical engineers (ASME)	An organization that publishes construction rules for boilers and pressure vessels, to ensure equipment safety over a reasonable service life. Canadian provinces enforce ASME codes as law.
American welding society (AWS)	A nonprofit organization, founded in 1919, in order to advance the science, technology and application of welding, joining and cutting processes, including brazing, soldering and thermal spraying.
Annealing	A heat treatment used to soften metal, whereby a material is heated to a specific temperature, and then allowed to cool at a slow, controlled rate.
Arc welding	A group of welding processes wherein coalescence is produced by heating the base metal with an electric arc, with or without the application of pressure, and with or without the use of filler metal.
ASME	See *American society of mechanical engineers*.
ASME code section IX	A codebook published by the American Society of Mechanical Engineers that addresses safe weld joint design and construction.
AWS	See *American welding society*.
Babbitt	A white bearing metal of non-ferrous material. It can contain several tin-based alloys, mainly copper, antimony, tin, and lead.
Backing material	A material placed at the root of a weld joint to support the molten weld metal. This facilitates complete joint penetration, and eliminates burn-through. The material may or may not fuse into the joint.
Base metal	In welding, the metal pieces being joined together. Also called “parent metal.”
Basic oxygen furnace (BOF)	A large furnace for recycling steel and refining pig iron, used in the production of steel.
Black light	Electromagnetic radiation in the near-ultraviolet wavelength range.
Bleedout	In PT, the action of an entrapped liquid penetrant in surfacing from discontinuities to form visible indications.
BOF	See *basic oxygen furnace*.
Brass	A malleable alloy of copper and zinc in varying proportions. Lead may be added up to two percent to aid in machining.
Brazing	In welding, a joining process wherein metals are bonded together using a filler metal with a melting temperature greater than 450°C, but lower than the melting temperature of the base metal. The filler metal is distributed between the joint surfaces by capillary action.
Brinell hardness number	A number that represents the hardness of a material, determined through the use of a Brinell hardness tester.

Term	Definition
Brinell hardness test	A test to determine the hardness of a material, using a procedure and equipment developed by the Swedish engineer Johan Brinell.
Brittle	Susceptible to fracturing without first undergoing plastic deformation.
Brittleness	Having the mechanical property whereby a material will fracture without first undergoing plastic deformation.
Bronze	An alloy of copper containing up to around 20 percent tin, as well as other alloying agents such as aluminum and phosphorus.
Butt joint	A joint between two members aligned approximately in the same plane.
Canadian welding bureau (CWB)	The CWB is a certification body for the administration of Canadian Standards Association (CSA) welding related standards.
Case hardening	A process that results in a material being significantly harder on the surface than inside.
Cast iron	Any number of alloys of steel and carbon containing between 2 and 4 percent carbon.
Charpy test	A test to determine the impact strength or "toughness" of a material.
Colour contrast penetrant	A liquid penetrant that is characterized by an intense (usually red) colour.
Complete penetration	When weld metal extends fully from one face of the parent material to the opposite face. Also called "full penetration."
Concavity	The maximum distance from the face of a concave fillet weld perpendicular to a line joining the weld toes.
Consumable electrode	An arc-welding electrode that melts and provides filler metal to a weld joint.
Convexity	The maximum distance from the face of a convex fillet weld, perpendicular to a line joining the weld toes.
Couplant	A substance used between an ultrasonic transducer and test surface, to permit or improve transmission of ultrasonic energy.
Coupon	A representative specimen of a material used in tests to determine the material's properties.
Cupola furnace	A small blast furnace used to produce cast iron from scrap metal and pig iron.
CWB	See *Canadian welding bureau*.
DC electrode negative (DCEN)	In shielded metal arc welding, the arrangement of direct current arc welding leads in which the electrode is the negative pole and the work piece is the positive pole of the welding circuit. Also called "straight polarity."
DC electrode positive (DCEP)	In shielded metal arc welding, the arrangement of direct current arc welding leads in which the electrode is the positive pole and the work piece is the negative pole of the welding circuit. Also called "reverse polarity."
DCEN	See *DC electrode negative*.
DCEP	See *DC electrode positive*.
Defect	One or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.
Developer	A material that is applied to the test surface to accelerate bleedout and to enhance the contrast of indications.
Discontinuity	A lack of continuity or cohesion; an intentional or unintentional interruption in the physical structure or configuration of a material or component.
Double-welded	A weld joint that is welded from both sides.

Term	Definition
Ductile	Able to be lengthened under tensile load without fracturing.
Ductile iron	A ductile form of cast iron where mechanically held carbon precipitates are in the form of small balls or "nodules".
Ductility	A mechanical property that enables the metal to be drawn or lengthened without fracture.
Dwell time	In PT, the total time that the penetrant is in contact with the test surface, including the time required for application.
Elasticity	Having the ability to deform under load, and return to its previous size and shape after the deforming load is removed.
Electromagnetic (eddy current) testing (ET)	A nondestructive test method for materials, including magnetic materials, that uses electromagnetic energy having frequencies less than those of visible light to yield information regarding the quality of testing material.
Equal pressure torch	A form of welding torch that uses fuel gas and oxygen supplies set to the same gas pressure.
False indication	An NDT indication that is interpreted to be caused by a discontinuity at a location where no discontinuity exists.
Ferrous	Containing the element iron.
Filler metal	The metal or alloy to be added when making a welded, brazed, or soldered joint.
Filler rod	A metal or alloy wire added to a weld joint when making a welded, brazed, or soldered joint.
Fillet weld	A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap joint, tee joint, or corner joint.
Fluorescence	The emission of visible radiation by a substance as a result of, and only during, the absorption of black light radiation.
Fluorescent liquid penetrant	A penetrant that emits visible radiation when excited by black light.
Full penetration	When weld metal extends fully from one face of the parent material to the opposite face. Also called "complete penetration."
Fully manual process	A welding process in which the rate of weld progression and the rate of filler material addition are both controlled by the person performing the weld.
Fusion welding	The melting together of filler metal and base metal, or of base metal only, to produce a weld.
Gamma ray	Electromagnetic penetrating radiation having its origin in the decay of a radioactive nucleus.
Gas metal arc welding (GMAW)	A semi-automatic welding process that uses the heat from an electric arc to melt the base metal, and a continuous consumable automatically-fed weld electrode as filler material. The process is performed with externally supplied shielding gas. (Formerly called "MIG welding.")
Gas tungsten arc welding (GTAW)	A fully manual arc welding process which uses the heat of an arc formed between a tungsten (non-consumable) electrode and the work pieces. Shielding is obtained from a gas or gas mixture. Pressure may or may not be used and filler metal may or may not be used. (Formerly called "TIG welding.")
GMAW	See *gas metal arc welding.*
Grey cast iron	A type of cast iron that contains mechanically held carbon precipitates, in the form of small graphite flakes. Grey cast iron is strong in compression, but relatively weak and brittle under tension.

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Term	Definition
Groove weld	A weld made in a groove formed between two members to be joined.
GTAW	See *gas tungsten-arc welding*.
Hardness	A mechanical property that refers to the ability of a material to resist penetration. Extremely hard materials cannot be chipped, filed or machined and can only be finished by grinding. Carbon steel tools and chilled cast iron are examples of hard materials.
HAZ	See *heat affected zone*.
Heat affected zone (HAZ)	That portion of the base metal which has not been melted, but whose mechanical properties or microstructures have been altered by the heat of welding or cutting.
Heliarc	A form of gas tungsten arc welding where helium is used as the shielding gas.
Image quality indicator (IQI)	In RT, a device whose demonstrated image provides visual or quantitative data to determine radiologic quality and sensitivity. Also called "penetrameter."
Inclusion	In welding, foreign solid matter trapped within a weld deposit.
Incomplete fusion	A weld discontinuity in which fusion did not occur between the weld metal and the fusion faces or the adjoining weld beads.
Incomplete penetration	A joint root condition in a groove weld in which weld metal does not extend through the joint thickness.
Indication	In NDE, evidence of a discontinuity that requires interpretation to determine its significance.
IQI	See *image quality indicator*.
Iron ore	Naturally occurring iron oxides, from which elemental iron can be derived.
Izod test	A test to determine the impact strength or "toughness" of a material.
Lamination	A type of discontinuity that has separation or weakness generally aligned parallel to the worked surface of a metal.
Lap joint	A joint between two overlapping members in parallel planes.
Liquid penetrant testing (PT)	A nondestructive test that uses suitable liquids that penetrate discontinuities open to the surface of solid materials and, after appropriate treatment, indicate the presence of discontinuities.
Magnetic particle testing (MT)	A nondestructive test method utilizing magnetic leakage fields and suitable indicating materials to disclose surface and near-surface discontinuity indications.
Malleability	A mechanical property that enables a material to be hammered or rolled under compressive load without fracturing.
Malleable cast iron	A malleable form of cast iron, which results when white cast iron is annealed.
Metal inert gas welding	See *gas metal arc welding*.
Methylacetylene-propadiene (MPS Gas)	A blend of fuel gases with a high flame temperature, used for welding or brazing. Also called MPS gas.
MIG	See *gas metal arc welding*.
MPS gas	See *methylacetylene-propadiene*.
Multi-pass weld	A weld joint made of several passes.
NDE	See *non-destructive examination*.

Term	Definition
Non-destructive examination (NDE)	The application of technical methods to examine materials or components in ways that do not impair future usefulness and serviceability, in order to detect, locate, measure, and evaluate flaws; to assess integrity, properties, and composition; and to measure geometric characteristics.
Non-ferrous	A pure metal other than iron, or an alloy that contains less than 50% iron.
Non-fusion welding	Welding that occurs without melting the base metal.
Offgas	Gas emitted from a chemical process as a by-product.
OFW	See *oxy-fuel gas welding*.
Oscilloscope	A device for viewing oscillations of electrical voltage or current, on the screen of a cathode ray tube or other visual display.
Overlap	The protrusion of weld metal beyond the weld toe or weld root.
Oxyacetylene	A welding, brazing, or cutting process that uses acetylene gas premixed with oxygen, to provide a flame hot enough to melt steel.
Oxy-fuel gas welding (OFW)	A group of welding processes which produce coalescence by heating materials with an oxyfuel gas flame, with or without the application of pressure, and with or without the use of filler metal.
Parent metal	In welding, the metal pieces being joined together. Also called “base metal.”
Pass	A single progression of a welding operation along a weld joint deposit. The result of a pass is a weld bead.
Penetrameter	See *image quality indicator*.
Penetrant	In PT, a solution or suspension of dye with suitable viscosity and surface-wetting ability for capillary action to occur.
Penetration	In welding, the depth that weld metal extends from the surface of the parent metal into a weld joint.
Piezoelectric effect	The ability of certain materials to generate an electric charge in response to applied mechanical stress, or to vibrate through the direct application of electric charge.
Pig iron	A hard, strong, and brittle alloy of iron and carbon used to make cast irons and steel.
Plain carbon steel	An alloy of iron and carbon, with 0.3% carbon or less, and no appreciable amount of other alloying agents.
Plastic	Easily shaped or molded.
Plasticity	A mechanical property that enables a material to be easily molded or shaped.
Porosity	Cavity-type discontinuities formed by gas entrapment during weld deposit solidification.
Post weld heat treatment	Any heat treatment subsequent to welding, which serves to restore desirable mechanical properties to the parent metal and the weld metal.
Preheating	The application of heat to the base metal immediately before a welding or cutting operation to prevent the formation of undesirable metallurgical structures within the heat-affected zone.
Radiographic testing (RT)	The use of X-rays or nuclear radiation, or both, to detect discontinuities in material, and to present their images on a recording medium.
Reinforcement	Weld metal in excess of the quantity required to fill a weld groove.
Repad	A metal plate welded into place around an opening in a boiler or pressure vessel, used to reinforce the shell where the opening was made. Short for “reinforcement pad.”

Term	Definition
Reverse polarity	In shielded metal arc welding, the arrangement of direct current arc welding leads in which the electrode is the positive pole and the work piece is the negative pole of the welding circuit. (Known as DCEP.)
Rockwell B hardness	A material hardness value determined using the Rockwell test method and equipment, and an indenter shaped as a ball.
Rockwell C hardness	A material hardness value determined using the Rockwell test method and equipment, and an indenter shaped as a diamond cone. This is a procedure for determining the hardness of very hard materials.
Rockwell hardness test	A material hardness test using the Rockwell test method and equipment.
Root face	The exposed surface of the root opening, on the side from which welding was done.
Root opening	The distance of the gap between the parent metal pieces prior to welding taking place.
Rutile	A reddish-brown mineral (Titanium dioxide (TiO_2)) used as a welding electrode coating. Rutile electrodes contain between 25 and 45% rutile, and produce a thick slag coating.
SAW	See *submerged arc welding*.
Semi-automatic arc welding	Arc welding with equipment which controls only the filler metal feed. The advance of the welding is manually controlled.
Shielded metal arc welding (SMAW)	A fully manual welding process that uses the heat from an electric arc to melt the base metal, and a consumable weld electrode as filler material. Also called “stick welding” or simply “arc welding.”
Shielding gas	An inert or semi-inert gas supplied to the weld puddle, and to the solidifying weldment, to provide protection from atmospheric gases such as oxygen, hydrogen, and water vapour, which will negatively affect the quality of the weld. The primary gases used for electric welding are argon (Ar), helium (He), nitrogen (N_2), and carbon dioxide (CO_2).
Shore hardness	A material hardness test using the Shore test method and an instrument called a Shore Scleroscope.
Silver brazing	A brazing process that uses silver-based alloys as filler metal. This form of brazing is commonly done to construct copper refrigerant and compressed air piping systems.
Single-welded	A weld joint welded from one side only.
SMAW	See *shielded metal arc welding*.
Soldering	In welding, a joining process wherein metals are bonded together using a non-ferrous filler metal with a melting temperature lower than 450°C. The filler metal is distributed between the joint surfaces by capillary action.
Steel	An alloy of iron and carbon containing between 0.05% and roughly 2% carbon.
Stick welding	A common name for “Shielded Metal Arc Welding.” A fully manual welding process that uses the heat from an electric arc to melt the base metal, and a consumable weld electrode as filler material.
Stinger	The hand piece for holding a consumable electrode when performing shielded metal arc welding.
Straight polarity	In shielded metal arc welding, the arrangement of direct current arc welding leads in which the electrode is the negative pole and the work piece is the positive pole of the welding circuit. Also called “DCEN.”

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Term	Definition
Strength	A mechanical property that refers to the ability of a material to support a load without fracturing. Expressed in Pascals.
Stress relief	A form of Post-Weld Heat Treatment.
Submerged arc welding (SAW)	An arc welding process that uses an arc or arcs between a bare metal electrode or electrodes and the weld pool. The arc and molten metal are shielded by a blanket of granular flux on the work pieces.
Tack weld	Small, intermittent welds made to hold components in place before full welding is begun.
Tee joint	A joint between two members located approximately at right angles to each other in the form of the letter "T."
TIG	See *gas tungsten arc welding*.
Toughness	A mechanical property that refers to the ability of a material to withstand repeated impact forces without fracturing.
Transducer (NDE)	In NDE, an electroacoustical device that uses a piezoelectric crystal element for converting electrical energy into acoustical energy and vice versa.
Tungsten inert gas	See *gas tungsten arc welding*.
Tup	A heavy metal piece used to asses material hardness when using a Shore Scleroscope.
Ultrasonic testing (UT)	A nondestructive method of examining materials by introducing ultrasonic waves into, through, or onto the surface of the article being examined and determining various attributes of the material from effects on the ultrasonic waves.
Ultrasound	Sound or other vibrations having an ultrasonic frequency, used in non-destructive examination.
Undercut	A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.
Visual testing (VT)	Non-destructive inspection of equipment and structures, using human senses unaided by specialized equipment.
Volumetric examination	A form of non-destructive examination to determine the three-dimensional situation of a sub-surface discontinuity. RT and UT are forms of volumetric examination.
Weld consumables	Items that are consumed during welding, such as filler material and shielding gas.
Weld leg	The distance from the joint root to the toe of the fillet weld.
Weld throat	The shortest distance between the weld root and the face of a fillet weld.
Welder operator	A person who operates automatic welding equipment.
White cast Iron	A hard, strong, and brittle form of cast iron, produced by chilling cast iron as it solidifies.
White metal	Any number of non-ferrous metal alloys, used for manufacturing bearings. White metals are made primarily from lead and tin, and may contain copper and antimony in small amounts.
Wrought iron	Essentially pure iron, with few impurities.
X-ray	An electromagnetic wave of high energy and very short wavelength, which is able to pass through many materials opaque to light.

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Additional Workspace

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