

FUNDAMENTALS OF WELDING

1- INTRODUCTION

The *term joining* is generally used for welding, brazing, soldering, and adhesive bonding, which form a permanent joint between the parts—a joint that cannot easily be separated. The term assembly usually refers to mechanical methods of fastening parts together. Some of these methods allow for easy disassembly, while others do not.

We begin our coverage of the joining and assembly processes with welding,

Welding is a materials joining process in which two or more parts are coalesced at their contacting surfaces by a suitable application of heat and/or pressure. Many welding processes are accomplished by heat alone, with no pressure applied; others by a combination of heat and pressure; and still others by pressure alone, with no external heat supplied. In some welding processes a filler material is added to facilitate coalescence. The assemblage of parts that are joined by welding is called a *weldment*.

Welding is most commonly associated with metal parts, but the process is also used for joining plastics. Our discussion of welding will focus on metals. Welding is a relatively new process (Historical Note 29.1). Its commercial and technological importance derives from the following:

- 1- Welding provides a permanent joint. The welded parts become a single entity.
- 2- The welded joint can be stronger than the parent materials if a filler metal is used that has strength properties superior to those of the parents, and if proper welding techniques are used.
- 3- Welding is usually the most economical way to join components in terms of material usage and fabrication costs. Alternative mechanical methods of assembly require more complex shape alterations (e.g., drilling of holes) and addition of fasteners (e.g., rivets or bolts). The resulting mechanical assembly is usually heavier than a corresponding weldment.
- 4- Welding is not restricted to the factory environment. It can be accomplished “in the field.”

Although welding has the advantages indicated above, it also has certain limitations and drawbacks (or potential drawbacks):

- 1- Most welding operations are performed manually and are expensive in terms of labor cost. Many welding operations are considered “skilled trades,” and the labor to perform these operations may be scarce.
- 2- Most welding processes are inherently dangerous because they involve the use of high energy.
- 3- Since welding accomplishes a permanent bond between the components, it does not allow for convenient disassembly. If the product must occasionally be disassembled (e.g., for repair or maintenance), then welding should not be used as the assembly method.
- 4- The welded joint can suffer from certain quality defects that are difficult to detect. The defects can reduce the strength of the joint.

Welding involves localized coalescence or joining together of two metallic parts at their faying surfaces. The faying surfaces are the part surfaces in contact or close proximity that are to be joined. Welding is usually performed on parts made of the same metal, but some welding operations can be used to join dissimilar metals.

2- TYPES OF WELDING PROCESSES

Some 50 different types of welding operations have been cataloged by the American Welding Society. They use various types or combinations of energy to provide the required power. We can divide the welding processes into two major groups: (1) fusion welding and (2) solid-state welding.

1-Fusion Welding

Fusion-welding processes use heat to melt the base metals. In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and strength to the

welded joint. A fusion-welding operation in which no filler metal is added is referred to as an autogenous weld. The fusion category includes the most widely used welding processes, which can be organized into the following general groups (initials in parentheses are designations of the American Welding Society):

Arc welding (AW). Arc welding refers to a group of welding processes in which heating of the metals is accomplished by an electric arc, as shown in **Figure 1**. Some arc welding operations also apply pressure during the process and most utilize a filler metal.

Resistance welding (RW). Resistance welding achieves coalescence using heat from electrical resistance to the flow of a current passing between the faying surfaces of two parts held together under pressure. included spot welding and seam welding, two joining methods widely used today in sheet metal working.

Oxyfuel gas welding (OFW). These joining processes use an oxyfuel gas, such as a mixture of oxygen and acetylene, to produce a hot flame for melting the base metal and filler metal, if one is used. Although Davy discovered acetylene gas early in the 1800s, oxyfuel gas welding required the subsequent development of torches for combining acetylene and oxygen around 1900. During the 1890s, hydrogen and natural gas were mixed with oxygen for welding, but the oxyacetylene flame achieved significantly higher temperatures. These three welding processes—arc welding, resistance welding, and oxyfuel gas welding—constitute by far the majority of welding operations performed today.

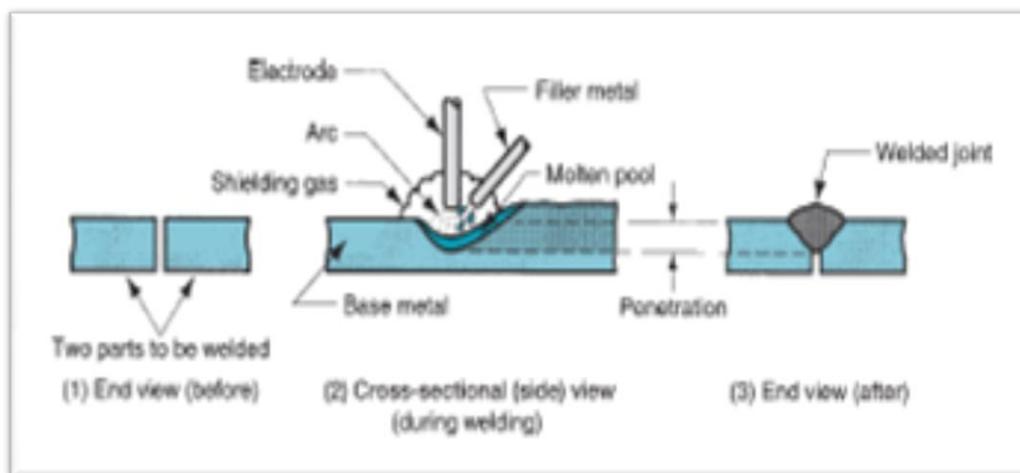


Figure 1 Basics of arc welding: (1) before the weld; (2) during the weld (the base metal is melted and filler metal is added to the molten pool); and (3) the completed weldment.

There are many variations of the arc-welding process.

Other fusion-welding processes. Other welding processes that produce fusion of the metals joined include electron beam welding and laser beam welding. Certain arc and oxyfuel processes are also used for cutting metals.

2- Solid-State Welding

Solid-state welding refers to joining processes in which coalescence results from application of pressure alone or a combination of heat and pressure. If heat is used, the temperature in the process is below the melting point of the metals being welded. No filler metal is utilized. Representative welding processes in this group include:

Diffusion welding (DFW). Two surfaces are held together under pressure at an elevated temperature and the parts coalesce by solid-state diffusion.

Friction welding (FRW). Coalescence is achieved by the heat of friction between two surfaces.

Ultrasonic welding (USW). Moderate pressure is applied between the two parts and an oscillating motion at ultrasonic frequencies is used in a direction parallel to the contacting surfaces. The combination of normal and vibratory forces results in shear stresses that remove surface films and achieve atomic bonding of the surfaces.

3- WELDING AS A COMMERCIAL OPERATION

The principal applications of welding are (1) construction, such as buildings and bridges; (2) piping, pressure vessels, boilers, and storage tanks; (3) shipbuilding; (4) aircraft and aerospace; and (5) automotive and railroad .

Welding is performed in a variety of locations and in a variety of industries. Owing to its versatility as an assembly technique for commercial products, many welding operations are performed in factories. However, several of the traditional processes, such as arc welding and oxyfuel gas welding, use equipment that can be readily moved, so these operations are not limited to the factory. They can be performed at construction sites, in shipyards, at customers' plants, and in automotive repair shops.

Most welding operations are labor intensive. For example, arc welding is usually performed by a skilled worker, *called a welder*, who manually controls the path or placement of the weld to join individual parts into a larger unit. In factory operations in which arc welding is manually performed, the welder often works with a second worker, called a *fitter*.

It is the fitter's job to arrange the individual components for the welder prior to making the weld. Welding fixtures and positioners are used for this purpose.

A *welding fixture* is a device for clamping and holding the components in fixed position for welding. It is custom fabricated for the particular geometry of the weldment and therefore must be economically justified on the basis of the quantities of assemblies to be produced.

A *welding positioner* is a device that holds the parts and also moves the assemblage to the desired position for welding. This differs from a welding fixture that only holds the parts in a single fixed position. The desired position is usually one in which the weld path is flat and horizontal.

The Safety Issue Welding is inherently dangerous to human workers. Strict safety precautions must be practiced by those who perform these operations. The high temperatures of the molten metals in welding are an obvious danger. In gas welding, the fuels (e.g., acetylene) are a fire hazard. Most of the processes use high energy to cause melting of the part surfaces to be joined. In many welding processes, electrical power is the source of thermal energy, so there is the hazard of electrical shock to the worker. Certain welding processes have their own particular perils.

In arc welding, for example, ultraviolet radiation is emitted that is injurious to human vision. A special helmet that includes a dark viewing window must be worn by the welder. This window filters out the dangerous radiation but is so dark that it renders the welder virtually blind, except when the arc is struck. Sparks, spatters of molten metal, smoke, and fumes add to the risks associated with welding operations. Ventilation facilities must be used to exhaust the dangerous fumes generated by some of the fluxes and molten metals used in welding. If the operation is performed in an enclosed area, special ventilation suits or hoods are required.

Automation in Welding Because of the hazards of manual welding, and in efforts to increase productivity and improve product quality, various forms of mechanization and automation have been developed.

The categories include machine welding, **automatic welding, and robotic welding.**

Machine welding can be defined as mechanized welding with equipment that performs the operation under the continuous supervision of an operator. It is normally accomplished by a welding head that is moved by mechanical means relative to a stationary work, or by moving the work relative to a stationary welding head. The human worker must continually observe and interact with the equipment to control the operation.

If the equipment is capable of performing the operation without control by a human operator, it is referred to as automatic welding. A human worker is usually present to oversee the process and detect variations from normal conditions. What distinguishes automatic welding from machine welding is a weld cycle controller to regulate the arc movement and workpiece positioning without continuous human attention. Automatic welding requires a welding fixture and/or positioner to position the work relative to the welding head. It also requires a higher degree of consistency and accuracy in the component parts used in the weldment. For these reasons, automatic welding can be justified only for large quantity production.

In robotic welding, an industrial robot or programmable manipulator is used to automatically control the movement of the welding head relative to the work. The versatile reach of the robot arm permits the use of relatively simple fixtures, and the robot's capacity to be reprogrammed for new part configurations allows this form of automation to be justified for relatively low production quantities. A typical robotic arc welding cell consists of two welding fixtures and a human fitter to load and unload parts while the robot welds. In addition to arc welding, industrial robots are also used in automobile final assembly plants to perform resistance welding on car bodies.

Welding produces a solid connection between two pieces, called a weld joint.

A **weld joint** is the junction of the edges or surfaces of parts that have been joined by welding. This section covers two classifications related to weld joints: (1) types of joints and (2) the types of welds used to join the pieces that form the joints.

4- TYPES OF JOINTS

There are five basic types of joints for bringing two parts together for joining. The five joint types are not limited to welding; they apply to other joining and fastening techniques as well.

With reference to **Figure 2**, the five joint types can be defined as follows:

(a) **Butt joint**. In this joint type, the parts lie in the same plane and are joined at their edges.

(b) **Corner joint**. The parts in a corner joint form a right angle and are joined at the corner of the angle.

(c) **Lap joint**. This joint consists of two overlapping parts.

(d) **Tee joint**. In a tee joint, one part is perpendicular to the other in the approximate shape of the letter "T."

(e) **Edge joint**. The parts in an edge joint are parallel with at least one of their edges in common, and the joint is made at the common edge(s).

5- TYPES OF WELDS

Each of the preceding joints can be made by welding. It is appropriate to distinguish between the joint type and the way in which it is welded—the weld type. Differences among weld types are in geometry (joint type) and welding process.

A **fillet weld** is used to fill in the edges of plates created by corner, lap, and tee joints, as in **Figure 3**. Filler metal is used to provide a cross section approximately the shape of a right triangle. It is the most common weld type in arc and oxyfuel welding because it requires minimum edge preparation—the basic square edges of the parts are used. Fillet welds can be single or double (i.e., welded on one side or both) and can be continuous or intermittent (i.e., welded along the entire length of the joint or with unwelded spaces along the length). Groove welds usually require that the edges of the parts be shaped into a groove to facilitate weld penetration. The grooved shapes include square, bevel, V, U, and J, in **Figure 2** Five basic types of joints: (a) butt, (b) corner, (c) lap, (d) tee, and (e) edge.

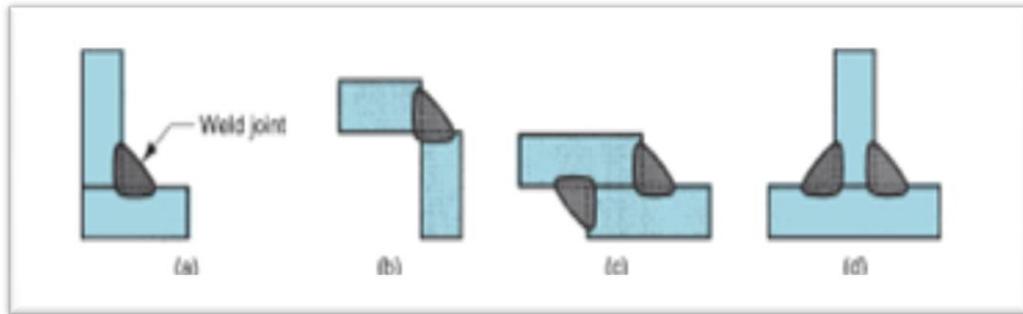
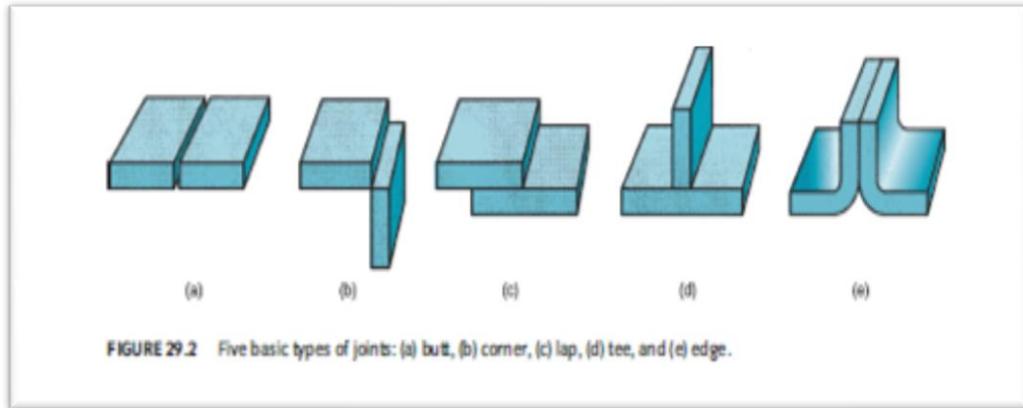


Figure 3 Various forms of fillet welds: (a) inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; and (d) double fillet tee joint. Dashed lines show the original part edges.

Single or double sides, as shown in **Figure 4**. Filler metal is used to fill in the joint, usually by arc or oxyfuel welding. Preparation of the part edges beyond the basic square edge, although requiring additional processing, is often done to increase the strength of the welded joint or where thicker parts are to be welded. Although most closely associated with a butt joint, groove welds are used on all joint types except lap.

Plug welds and slot welds are used for attaching flat plates, as shown in **Figure 5**, using one or more holes or slots in the top part and then filling with filler metal to fuse the two parts together.

Spot welds and seam welds, used for lap joints, are diagrammed in **Figure 6**. A spot weld is a small fused section between the surfaces of two sheets or plates. Multiple spot welds are typically required to join the parts. It is most closely associated with resistance welding. A seam weld is similar to a spot weld except it consists of a more or less continuously fused section between the two sheets or plates.

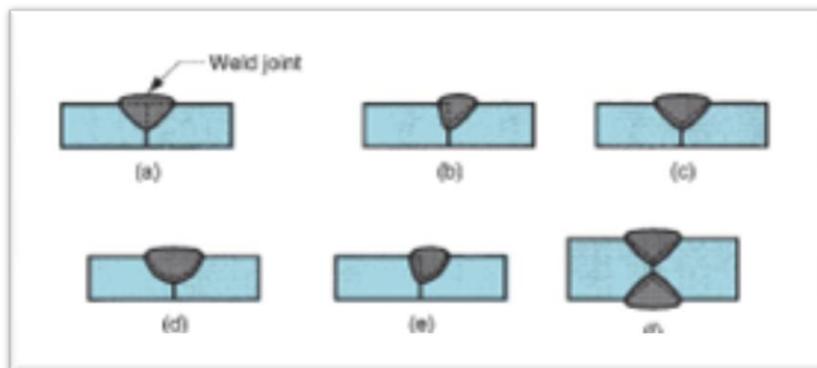


Figure 4 Some typical groove welds (a) square groove weld, one side; (b) single bevel groove weld; (c) single V-groove weld; (d) single U-groove weld; (e) single J-groove weld; (f) double V-groove weld for thicker sections. Dashed lines show the original part edges.

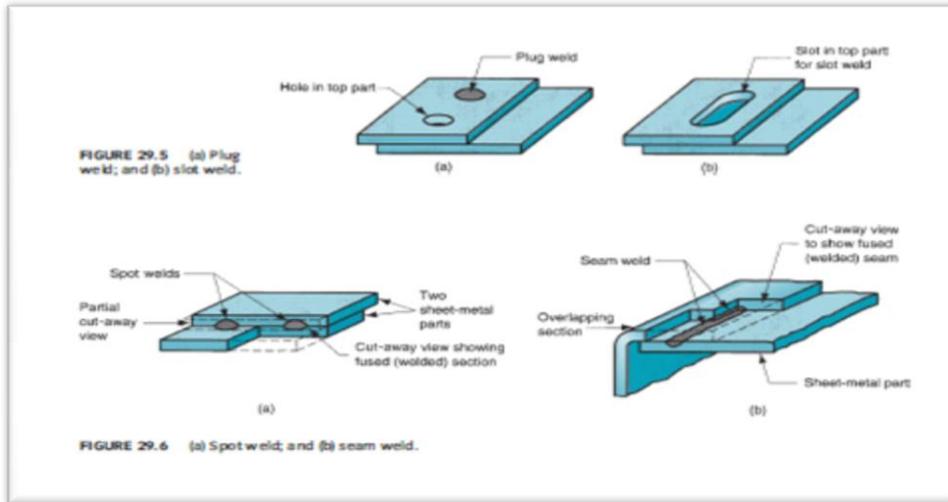


Figure 5 (a) Plug weld; and (b) slot weld. **Figure 6** a) Spot weld; and (b) seam weld.

Flange welds and surfacing welds are shown in **Figure 7**. A flange weld is made on the edges of two (or more) parts, usually sheet metal or thin plate, at least one of the parts being flanged as in **Figure 7** (a). A surfacing weld is not used to join parts, but rather to deposit filler metal onto the surface of a base part in one or more weld beads. The weld beads can be made in a series of overlapping parallel passes, thereby covering large areas of the base part. The purpose is to increase the thickness of the plate or to provide a protective coating on the surface.

Although several coalescing mechanisms are available for welding, fusion is by far the most common means. In this section, we consider the physical relationships that allow fusion welding to be performed. We first examine the issue of power density and its importance, and then we define the heat and power equations that describe a welding process.

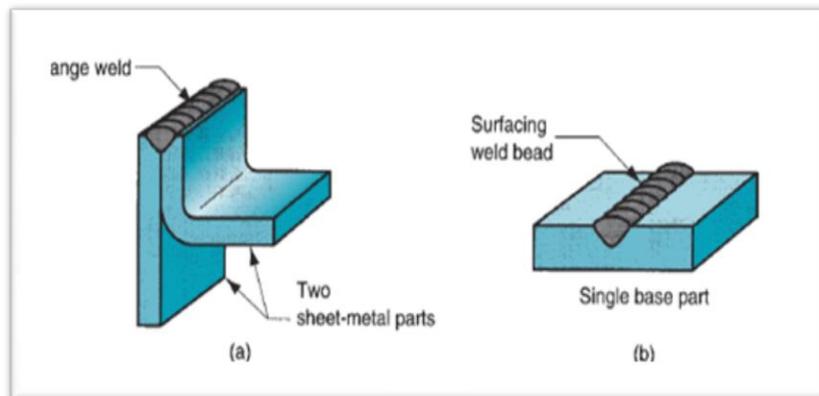


Figure 7 (a) Flange welds and (b) surfacing welds

6- POWER DENSITY

To accomplish fusion, a source of high-density heat energy is supplied to the faying surfaces, and the resulting temperatures are sufficient to cause localized melting of the base metals. If a filler metal is added, the heat density must be high enough to melt it also. Heat density can be defined as the power transferred to the work per unit surface area, W/mm^2 ($Btu/sec\text{-}in^2$). The time to melt the metal is inversely proportional to the power density. At low power densities, a significant amount of time is required to cause melting. If power density is too low, the heat is conducted into the work as rapidly as it is added at the surface, and melting never occurs. It has been found that the minimum power density required to melt most metals in welding is about $10 W/mm^2$ ($6 Btu/sec\text{-}in^2$). As heat density increases, melting time is reduced. If power density is too high—above around $105 W/mm^2$ ($60,000 Btu/sec\text{-}in^2$)—the localized temperatures vaporize the metal in the affected region. Thus,

there is a practical range of values for power density within which welding can be performed. Differences among welding processes in this range are (1) the rate at which welding can be performed and/or (2) the size of the region that can be welded.

Table 1 provides a comparison of power densities for the major fusion welding processes. Oxyfuel gas welding is capable of developing large amounts of heat, but the heat density is relatively low because it is spread over a large area. Oxyacetylene gas, the hottest of the OFW fuels, burns at a top temperature of around 3500_C (6300_F). By comparison, arc welding produces high energy over a smaller area, resulting in local temperatures of 5500_C to 6600_C (10,000_F–12,000_F). For metallurgical reasons, it is desirable to melt the metal with minimum energy, and high power densities are generally preferable.

Welding Process	Approximate Power Density	
	W/mm ²	Btu/sec-in ²
Oxyfuel welding	10	6
Arc welding	50	30
Resistanc welding	1000	600
Laser beam welding	9000	5000
Electron beam welding	10,000	6000

Power density can be computed as the power entering the surface divided by the corresponding surface area:

$$PD = P / A \dots\dots\dots(1)$$

where

PD = power density, W/mm² (Btu/sec-in²); P = power entering the surface, W(Btu/sec); and A= surface area over which the energy is entering,mm² (in²). The issue is more complicated than indicated by Eq. (29.1). One complication is that the power source (e.g., the arc) is moving in many welding processes, which results in preheating ahead of the operation and post heating behind it. Another complication is that power density is not uniform throughout the affected surface; it is distributed as a function of area.

7- HEAT BALANCE IN FUSION WELDING

The quantity of heat required to melt a given volume of metal depends on (1) the heat to raise the temperature of the solid metal to its melting point, which depends on the metal's volumetric specific heat, (2) the melting point of the metal, and (3) the heat to transform the metal from solid to liquid phase at the melting point, which depends on the metal's heat of fusion. To a reasonable approximation, this quantity of heat can be estimated by

$$Um = KT^2 m \dots\dots\dots(2)$$

where Um= the unit energy for melting (i.e., the quantity of heat required to melt a unit volume of metal starting from room temperature), J/mm³ (Btu/in³); Tm ¼ melting point of the metal on an absolute temperature scale, °K(°R); and K = constant whose value is 3.33x10⁻⁶ when the Kelvin scale is used (and K=1.467x10⁻⁵ for the Rankine temperature scale). Absolute melting temperatures for selected metals are presented in **Table 2**.

Table 2 Melting temperatures on the absolute temperature scale for selected metals.

TABLE 29.2 Melting temperatures on the absolute temperature scale for selected metals.					
Metal	Melting Temperature		Metal	Melting Temperature	
	$^{\circ}\text{K}^{\text{a}}$	$^{\circ}\text{R}^{\text{b}}$		$^{\circ}\text{K}^{\text{a}}$	$^{\circ}\text{R}^{\text{b}}$
Aluminum alloys	930	1680	Steels		
Cast iron	1530	2760	Low carbon	1760	3160
Copper and alloys			Medium carbon	1700	3060
Pure	1350	2440	High carbon	1650	2960
Brass, navy	1160	2090	Low alloy	1700	3060
Bronze (90 Cu-10 Sn)	1120	2010	Stainless steels		
Inconel	1660	3000	Austenitic	1670	3010
Magnesium	940	1700	Martensitic	1700	3060
Nickel	1720	3110	Titanium	2070	3730

Based on values in [2].
^aKelvin scale = Centigrade (Celsius) temperature + 273.
^bRankine scale = Fahrenheit temperature + 460.

Not all of the energy generated at the heat source is used to melt the weld metal. There are two heat transfer mechanisms at work, both of which reduce the amount of generated heat that is used by the welding process. The situation is depicted in **Figure 8**. The first mechanism involves the transfer of heat between the heat source and the surface of the work. This process has a certain heat transfer factor f_1 , defined as the ratio of the actual heat received by the workpiece divided by the total heat generated at the source. The second mechanism involves the conduction of heat away from the weld area to be dissipated throughout the work metal, so that only a portion of the heat transferred to the surface is available for melting. This melting factor f_2 is the proportion of heat received at the work surface that can be used for melting. The combined effect of these two factors is to reduce the heat energy available for welding as follows:

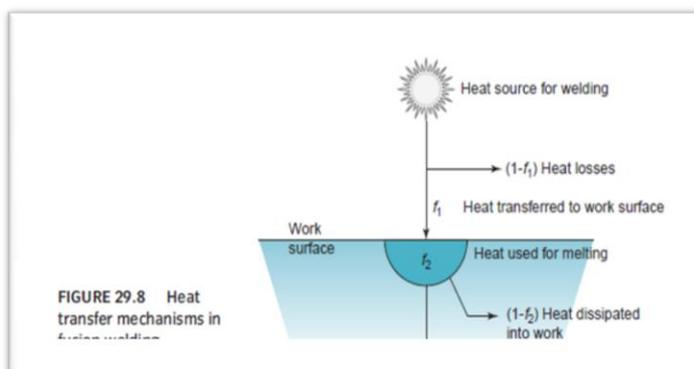
$$H_w = f_1 f_2 H \dots\dots\dots (3)$$

where

H_w = net heat available for welding, J (Btu), f_1 = heat transfer factor, f_2 = the melting factor, and H = the total heat generated by the welding process, J (Btu). The factors f_1 and f_2 range in value between zero and one. It is appropriate to separate f_1 and f_2 in concept, even though they act in concert during the welding process.

The heat transfer factor f_1 is determined largely by the welding process and the capacity to convert the power source (e.g., electrical energy) into usable heat at the work surface. Arc-welding processes are relatively efficient in this regard, while oxyfuel gas-welding processes are relatively inefficient.

The melting factor f_2 depends on the welding process, but it is also influenced by the thermal properties of the metal, joint configuration, and work thickness. Metals with high thermal conductivity, such as aluminum and copper, present a problem in welding because of the rapid dissipation of heat away from the heat contact area. The problem is exacerbated by welding heat sources with low energy densities (e.g., oxyfuel welding) because the heat input is spread over a larger area, thus facilitating conduction into the work. In general, a high power density combined with a low conductivity work material results in a high melting factor .



We can now write a balance equation between the energy input and the energy needed for welding:

$$H_w = U_m V \dots\dots\dots(4)$$

where

H_w = net heat energy used by the welding operation, J (Btu); U_m = unit energy required to melt the metal, J/mm³ (Btu/in³); and V = the volume of metal melted, mm³ (in³).

Most welding operations are rate processes; that is, the net heat energy H_w is delivered at a given rate, and the weld bead is made at a certain travel velocity. This is characteristic for example of most arc-welding, many oxyfuel gas-welding operations, and even some resistance welding operations. It is therefore appropriate to express Eq. (30) as a rate balance equation:

$$RH_w = U_m RWV \dots\dots\dots(5)$$

Where

RH_w = rate of heat energy delivered to the operation for welding, J/s = W (Btu/min); and

RWV = volume rate of metal welded, mm³/s (in³/min). In the welding of a continuous bead, the volume rate of metal welded is the product of weld area A_w and travel velocity v . Substituting these terms into the above equation, the rate balance equation can now be expressed as

$$RH_w = f_1 f_2 RH = U_m A_w v \dots\dots\dots(6)$$

Where

f_1 and f_2 are the heat transfer and melting factors; RH = rate of input energy generated by the welding power source, W (Btu/min); A_w = weld cross-sectional area, mm² (in²); and v = the travel velocity of the welding operation, mm/s (in/min).

8- Features of A Fusion - Welded Joints

Most weld joints are fusion welded. As illustrated in the cross-sectional view of **Figure 9** (a), a typical fusion-weld joint in which filler metal has been added consists of several zones: **(1) fusion zone, (2) weld interface, (3) heat-affected zone, and (4) unaffected base metal zone.**

The fusion zone consists of a mixture of filler metal and base metal that have completely melted. This zone is characterized by a high degree of homogeneity among the component metals that have been melted during welding. The mixing of these components is motivated largely by convection in the molten weld pool. Solidification in the fusion zone has similarities to a casting process. In 8significant difference between solidification in casting and in welding is that epitaxial grain growth occurs in welding. The reader may recall that in casting, the metallic grains are formed from the melt by nucleation of solid particles at the mold wall, followed by grain growth. In welding, by contrast, the nucleation stage of solidification is avoided by the mechanism of epitaxial grain growth, in which atoms from the molten pool solidify on preexisting lattice sites of the adjacent solid base metal.

Consequently, the grain structure in the fusion zone near the heat-affected zone tends to mimic the crystallographic orientation of the surrounding heat-affected zone. Further into the fusion zone, a preferred orientation develops in which the grains are roughly perpendicular to the boundaries of the weld interface. The resulting structure in the solidified fusion zone tends to feature coarse columnar grains, as depicted in **Figure 9(b)**. The grain structure depends on various factors,

including welding process, metals being welded (e.g., identical metals vs. dissimilar metals welded), whether a filler metal is used, and the feed rate at which welding is accomplished.

The second zone in the weld joint is **the weld interface**, a narrow boundary that separates the fusion zone from the heat-affected zone. The interface consists of a thin band of base metal that was melted or partially melted (localized melting within the grains) during the welding process but then immediately solidified before any mixing with the metal in the fusion zone. Its chemical composition is therefore identical to that of the base metal.

The third zone in the typical fusion weld is **the heat-affected zone (HAZ)**. The metal in this zone has experienced temperatures that are below its melting point, yet high enough to cause microstructural changes in the solid metal. The chemical composition in the heat-affected zone is the same as the base metal, but this region has been heat treated due to the welding temperatures so that its properties and structure have been altered.

The amount of metallurgical damage in the HAZ depends on factors such as the amount of heat input and peak temperatures reached, distance from the fusion zone, length of time the metal has been subjected to the high temperatures, cooling rate, and the metal's thermal properties. The effect on mechanical properties in the heat-affected zone is usually negative, and it is in this region of the weld joint that welding failures often occur.

As the distance from the fusion zone increases, the **unaffected base metal zone** is finally reached, in which no metallurgical change has occurred. Nevertheless, the base metal surrounding the HAZ is likely to be in a state of high residual stress, the result of shrinkage in the fusion zone.

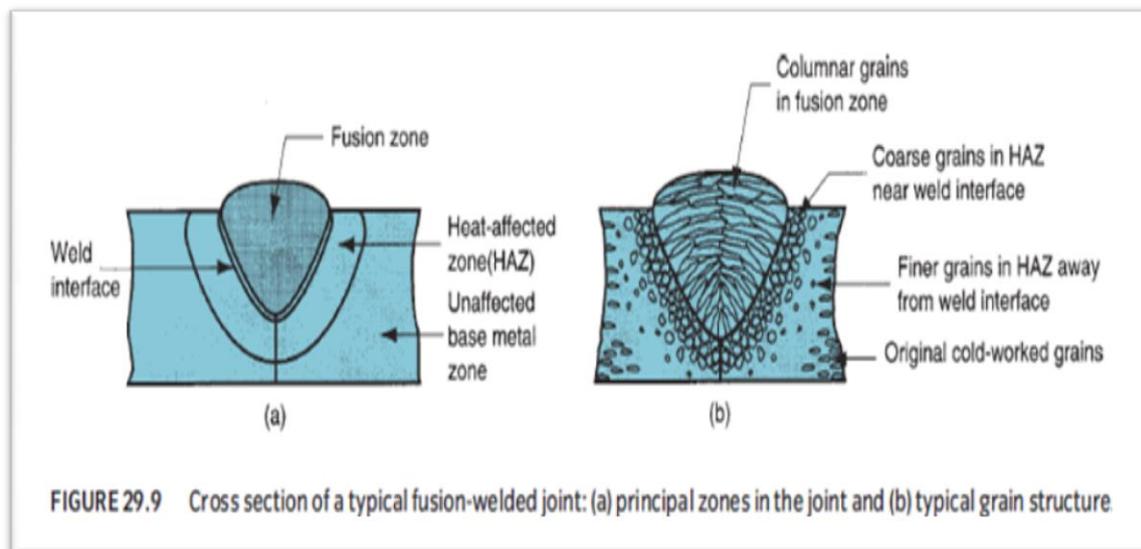


FIGURE 29.9 Cross section of a typical fusion-welded joint: (a) principal zones in the joint and (b) typical grain structure

Reference

Mikell P. Groover , " Fundamentals of Modern Manufacturing ,Materials ,Processes ,and Systems" ,4th edition, JOHN WILEY & SONS, INC.,2010

1-Fusion Welding Processes

1.1 Fusion Welding Processes

Fusion welding is a joining process that uses fusion of the base metal to make the weld. The three major types of fusion welding processes are as follows:

1- Gas welding:

Oxyacetylene welding (OAW)

2- Electric Arc welding:

Shielded metal arc welding (SMAW)

Gas-tungsten arc welding (GTAW)

Plasma arc welding (PAW)

Gas-metal arc welding (GMAW)

Flux-cored arc welding (FCAW)

Submerged arc welding (SAW)

Electroslag welding (ESW)

3. High-energy beam welding:

Electron beam welding (EBW)

Laser beam welding (LBW)

Since there is no arc involved in the electroslag welding process, it is not exactly an arc welding process. For convenience of discussion, it is grouped with arc welding processes.

1.2 Power Density of Heat Source

Consider directing a 1.5-kW hair drier very closely to a 304 stainless steel sheet 1.6mm (1/16 in.) thick. Obviously, the power spreads out over an area of roughly 50mm (2in.) diameter, and the sheet just heats up gradually but will not melt. With GTAW at 1.5kW, however, the arc concentrates on a small area of about 6mm (1/4 in.) diameter and can easily produce a weld pool. This example clearly demonstrates the importance of the power density of the heat source in welding.

The heat sources for the gas, arc, and high-energy beam welding processes are a gas flame, an electric arc, and a high-energy beam, respectively. The power density increases from a gas flame to an electric arc and a high-energy beam. As shown in **Figure 1.1**, as the power density of the heat source increases, the heat input to the workpiece that is required for welding decreases. The portion of the workpiece material exposed to a gas flame heats up so slowly that, before any melting occurs, a large amount of heat is already conducted away into the bulk of the workpiece. Excessive heating can cause damage to the workpiece, including weakening and distortion. On the contrary, the same material exposed to a sharply focused electron or laser beam can melt or even vaporize to form a deep *keyhole* instantaneously, and before much heat is conducted away into the bulk of the workpiece, welding is completed (1).

Therefore, the advantages of increasing the power density of the heat source are deeper weld penetration, higher welding speeds, and better weld quality with less damage to the workpiece, as indicated in **Figure 1.1**. **Figure 1.2** shows that the weld strength (of aluminum alloys) increases as the heat input per unit length of the weld per unit thickness of the workpiece decreases (2).

Figure 1.3a shows that angular distortion is much smaller in EBW than in GTAW (2).

Unfortunately, as shown in **Figure 1.3b**, the costs of laser and electron beam welding machines are very high (2).

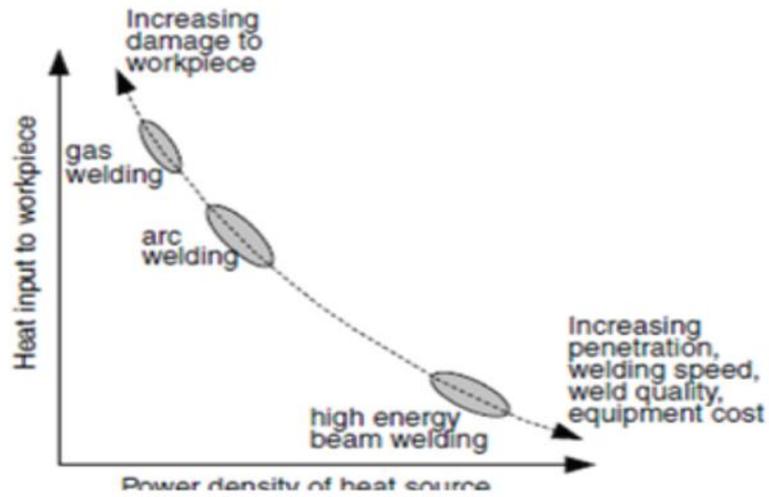


Figure 1.1 Variation of heat input to the workpiece with power density of the heat source.

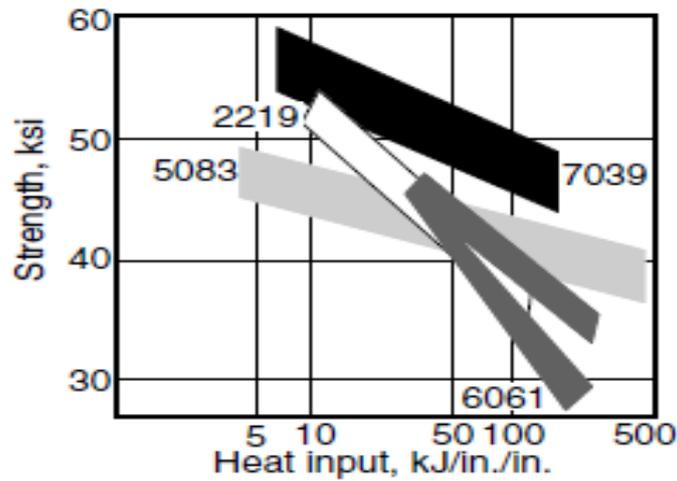


Figure 1.2 Variation of weld strength with heat input per unit length of weld per unit thickness of workpiece. Reprinted from Mendez and Eagar (2).

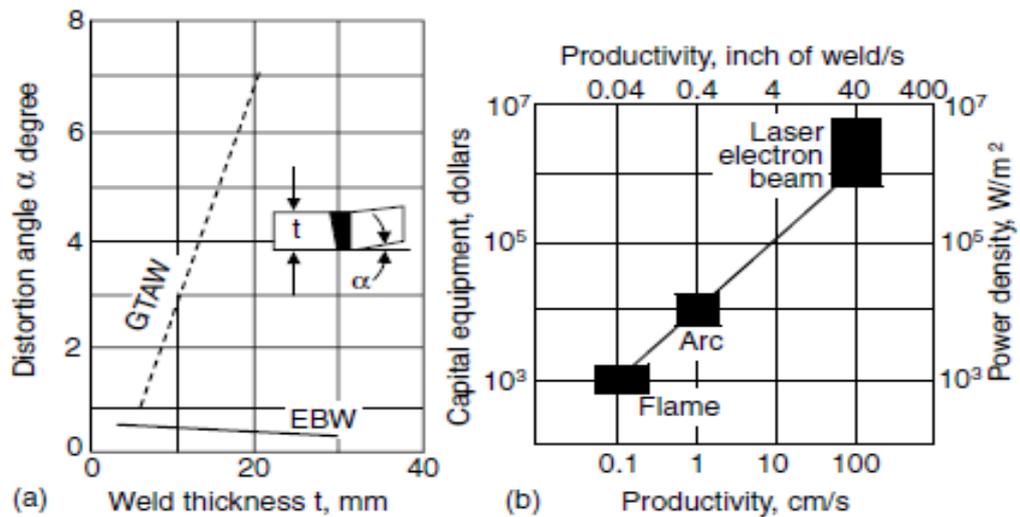


Figure 1.3 Comparisons between welding processes: (a) angular distortion; (b) capital equipment cost. Reprinted from Mendez and Eagar (2).

1.3 Welding Processes and Materials

Table 1.1 summarizes the fusion welding processes recommended for carbon steels, low-alloy steels, stainless steels, cast irons, nickel-base alloys, and aluminum alloys (3). For one example, GMAW can be used for all the materials of almost all thickness ranges while GTAW is mostly for thinner workpieces. For another example, any arc welding process that requires the use of a flux, such as SMAW, SAW, FCAW, and ESW, is not applicable to aluminum alloys.

Material	Thickness ^b	SMAW	SAW	GMAW	FCAW	GTAW	PAW	ESW	OPW	EBW	LBW
Carbon steels	S	X	X	X		X		X	X	X	X
	I	X	X	X	X	X		X	X	X	X
	M	X	X	X	X			X	X	X	
	T	X	X	X				X	X	X	
Low-alloy steels	S	X	X	X	X	X		X		X	X
	I	X	X	X	X	X		X		X	X
	M	X	X	X	X			X		X	
	T	X	X	X				X		X	
Stainless steels	S	X	X	X	X	X	X		X		X
	I	X	X	X	X	X			X		X
	M	X	X	X	X				X		
	T	X	X	X				X		X	
Cast iron	I	X							X	X	
	M	X						X	X		
	T	X						X	X		
Nickel and alloys	S	X		X		X	X	X		X	X
	I	X		X		X		X		X	X
	M	X		X						X	
	T	X		X						X	
Aluminum and alloys	S			X		X	X		X		X
	I			X		X			X		X
	T			X		X			X		X

* Process code: SMAW, shielded metal arc welding; SAW, submerged arc welding; GMAW, gas-metal arc welding; FCAW, gas-metal arc welding; GTAW, gas-tungsten arc welding; PAW, plasma arc welding; ESW, electron beam welding; OPW, oxygen fuel gas welding; EBW, electron beam welding; LBW, laser beam welding.

^b Abbreviations: S, sheet, up to 3mm (1/8 in.); I, intermediate, 3–6mm (1/4–1/2 in.); M, medium, 6–19mm (1/4–3/4 in.); T, thick, 19mm (3/4 in.) and up. X, recommended.

Source: *Welding Handbook* (3).

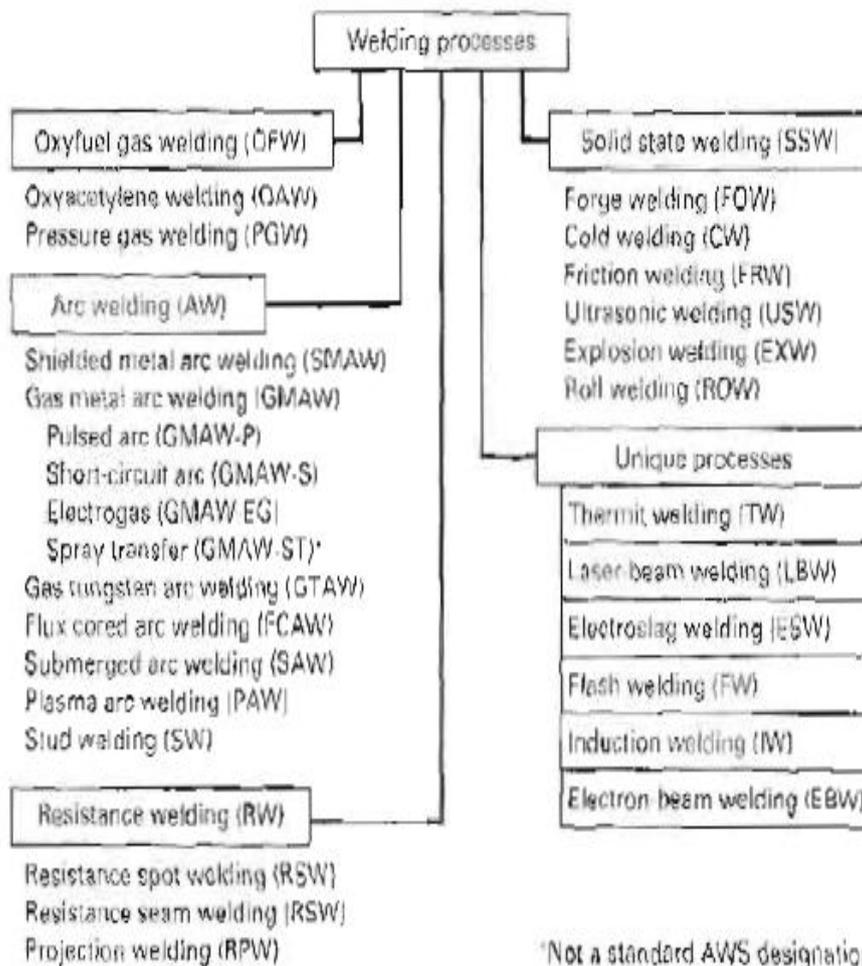


Figure 1.4 classification of common welding processes along with the AWS designations

Table 1.2

TABLE 30-1 Classification of Common Welding Processes by Rate of Heat Input	
Low Rate of Heat Input Oxyfuel welding (OFW) Electroslag welding (ESW) Flash welding (FW)	High Rate of Heat Input Plasma arc welding (PAW) Electron-beam welding (EBW) Laser welding (LBW) Spot and seam resistance welding (RW) Percussion welding
Moderate Rate of Heat Input	
Shielded metal arc welding (SMAW) Flux cored arc welding (FCAW) Gas metal arc welding (GMAW) Submerged arc welding (SAW) Gas tungsten arc welding (GTAW)	

Reference : DeGarmos , Materials and Processes in Manufacturing ,
10th edition ,John Wiley and Sons Inc. ,2008

2 - OXYACETYLENE WELDING

2.1 The Process

Gas welding is a welding process that melts and joins metals by heating them with a flame caused by the reaction between a fuel gas and oxygen. Oxyacetylene welding (OAW), shown in **Figure 2.1.**, is the most commonly used gas welding process because of its high flame temperature. A flux may be used to deoxidize and cleanse the weld metal. The flux melts, solidifies, and forms a slag skin on the resultant weld metal. **Figure 2.2** shows three different types of flames in oxyacetylene welding: neutral, reducing, and oxidizing (4), which are described next.

2.2 Three Types of Flames

A. Neutral Flame This refers to the case where oxygen (O_2) and acetylene (C_2H_2) are mixed in equal amounts and burned at the tip of the welding torch. A short inner cone and a longer outer envelope characterize a neutral flame (**Figure 2.2a**). The inner cone is the area where the primary combustion takes place through the chemical reaction between O_2 and C_2H_2 , as shown in **Figure 2.3**. The heat of this reaction accounts for about two-thirds of the total heat generated. The products of the primary combustion, CO and H_2 , react with O_2 from the surrounding air and form CO_2 and H_2O . This is the secondary combustion, which accounts for about one-third of the total heat generated. The area where this secondary combustion takes place is called the outer envelope.

It is also called the protection envelope since CO and H_2 here consume the O_2 entering from the surrounding air, thereby protecting the weld metal from oxidation. For most metals, a neutral flame is used.

B. Reducing Flame When excess acetylene is used, the resulting flame is called a reducing flame. The combustion of acetylene is incomplete. As a result, a greenish acetylene feather between the inert cone and the outer envelope characterizes a reducing flame (**Figure 2.2b**). This flame is reducing in nature and is desirable for welding aluminum alloys because aluminum oxidizes easily. It is also good for welding high-carbon steels (also called carburizing flame in this case) because excess oxygen can oxidize carbon and form CO gas porosity in the weld metal.

C. Oxidizing Flame When excess oxygen is used, the flame becomes oxidizing because of the presence of unconsumed oxygen. A short white inner cone characterizes an oxidizing flame (**Figure 2.2c**). This flame is preferred when welding brass because copper oxide covers the weld pool and thus prevents zinc from evaporating from the weld pool.

2.3 Advantages and Disadvantages

The main advantage of the oxyacetylene welding process is that the equipment is simple, portable, and inexpensive. Therefore, it is convenient for maintenance and repair applications. However, due to its limited power density, the welding speed is very low and the total heat input per unit length of the weld is rather high, resulting in large heat-affected zones and severe distortion. The oxyacetylene welding process is not recommended for welding reactive metals such as titanium and zirconium because of its limited protection power.

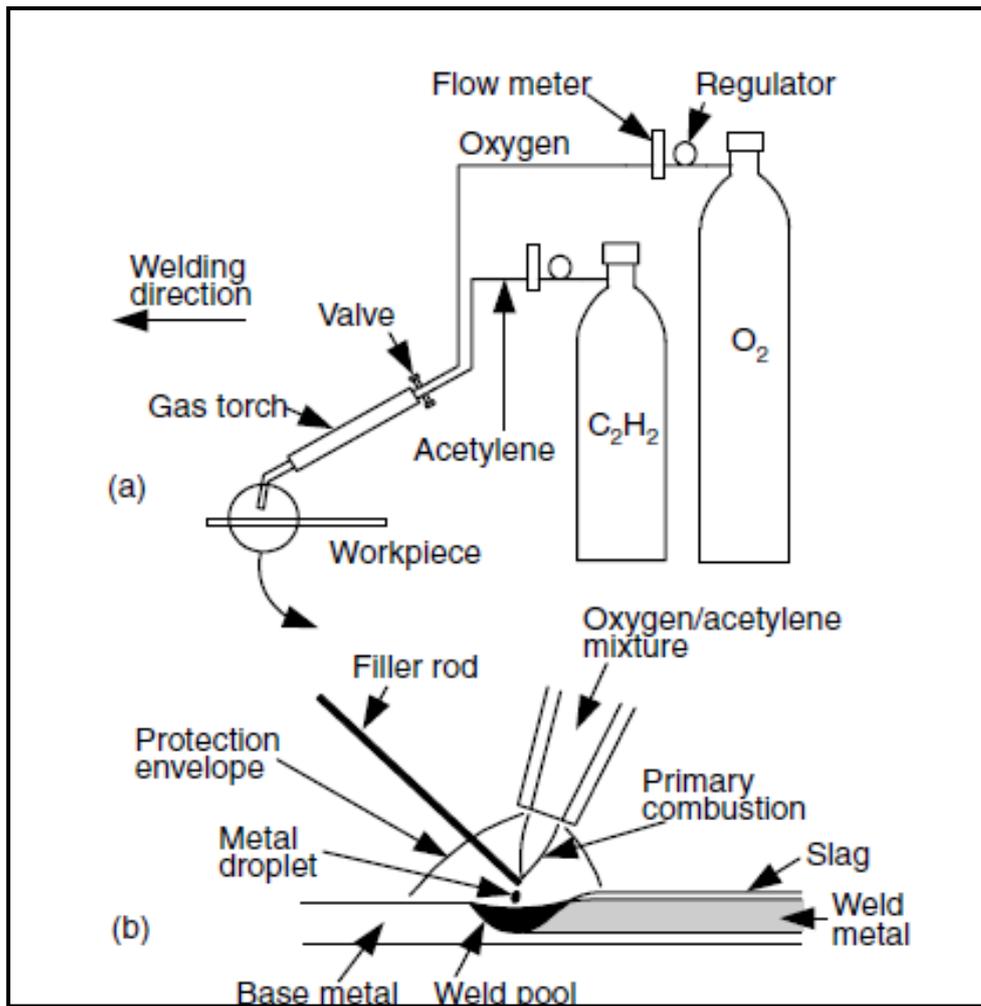


Figure 2.1 Oxyacetylene welding: (a) overall process; (b) welding area enlarged.

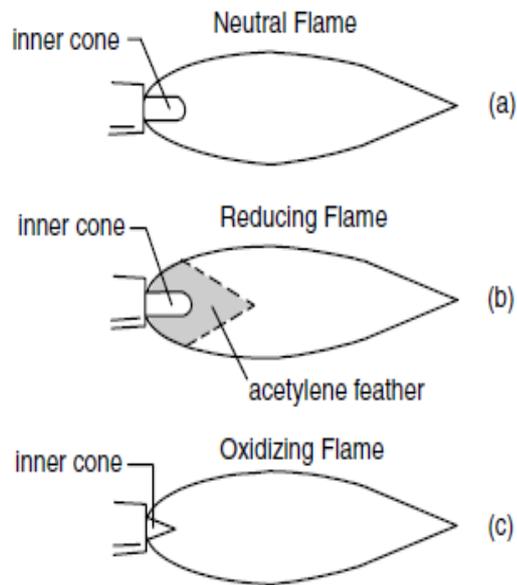


Figure 1.8 Three types of flames in oxyacetylene welding. Modified from *Welding Journal* (4). Courtesy of American Welding Society.

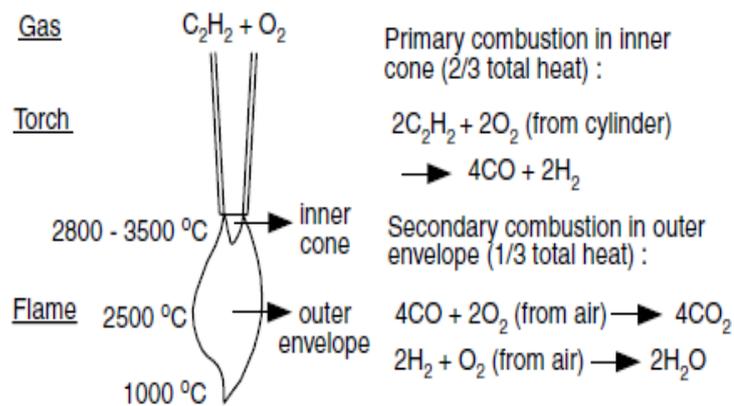


Figure 2.3 Chemical reactions and temperature distribution in a neutral oxyacetylene flame

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1-Fusion Welding Processes

1.1 Fusion Welding Processes

Fusion welding is a joining process that uses fusion of the base metal to make the weld. The three major types of fusion welding processes are as follows:

1- Gas welding:

Oxyacetylene welding (OAW)

2- Electric Arc welding:

Shielded metal arc welding (SMAW)

Gas-tungsten arc welding (GTAW)

Plasma arc welding (PAW)

Gas-metal arc welding (GMAW)

Flux-cored arc welding (FCAW)

Submerged arc welding (SAW)

Electroslag welding (ESW)

3. High-energy beam welding:

Electron beam welding (EBW)

Laser beam welding (LBW)

Since there is no arc involved in the electroslag welding process, it is not exactly an arc welding process. For convenience of discussion, it is grouped with arc welding processes.

1.2 Power Density of Heat Source

Consider directing a 1.5-kW hair drier very closely to a 304 stainless steel sheet 1.6mm (1/16 in.) thick. Obviously, the power spreads out over an area of roughly 50mm (2in.) diameter, and the sheet just heats up gradually but will not melt. With GTAW at 1.5kW, however, the arc concentrates on a small area of about 6mm (1/4 in.) diameter and can easily produce a weld pool. This example clearly demonstrates the importance of the power density of the heat source in welding.

The heat sources for the gas, arc, and high-energy beam welding processes are a gas flame, an electric arc, and a high-energy beam, respectively. The power density increases from a gas flame to an electric arc and a high-energy beam. As shown in **Figure 1.1**, as the power density of the heat source increases, the heat input to the workpiece that is required for welding decreases. The portion of the workpiece material exposed to a gas flame heats up so slowly that, before any melting occurs, a large amount of heat is already conducted away into the bulk of the workpiece. Excessive heating can cause damage to the workpiece, including weakening and distortion. On the contrary, the same material exposed to a sharply focused electron or laser beam can melt or even vaporize to form a deep *keyhole* instantaneously, and before much heat is conducted away into the bulk of the workpiece, welding is completed (1).

Therefore, the advantages of increasing the power density of the heat source are deeper weld penetration, higher welding speeds, and better weld quality with less damage to the workpiece, as indicated in **Figure 1.1**. **Figure 1.2** shows that the weld strength (of aluminum alloys) increases as the heat input per unit length of the weld per unit thickness of the workpiece decreases (2).

Figure 1.3a shows that angular distortion is much smaller in EBW than in GTAW (2).

Unfortunately, as shown in **Figure 1.3b**, the costs of laser and electron beam welding machines are very high (2).

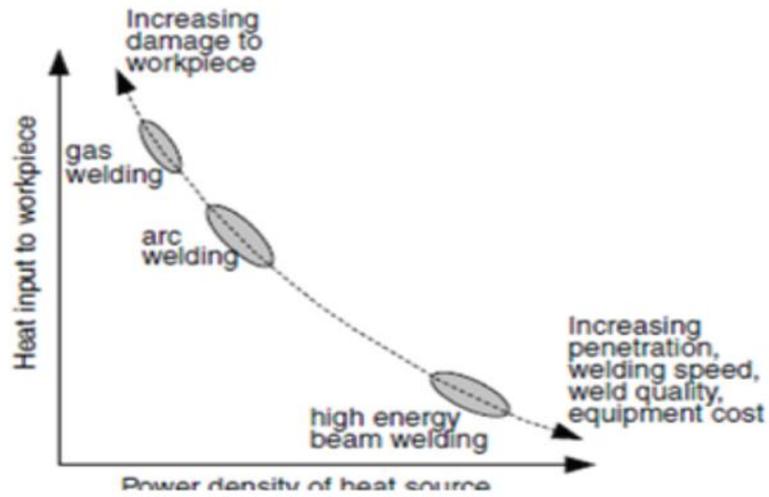


Figure 1.1 Variation of heat input to the workpiece with power density of the heat source.

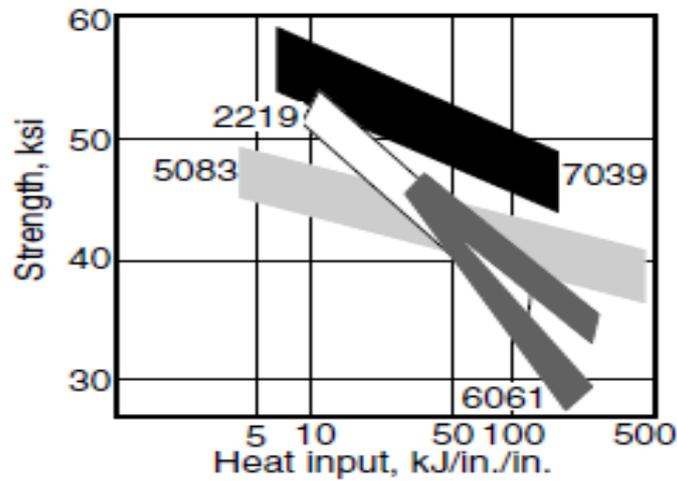


Figure 1.2 Variation of weld strength with heat input per unit length of weld per unit thickness of workpiece. Reprinted from Mendez and Eagar (2).

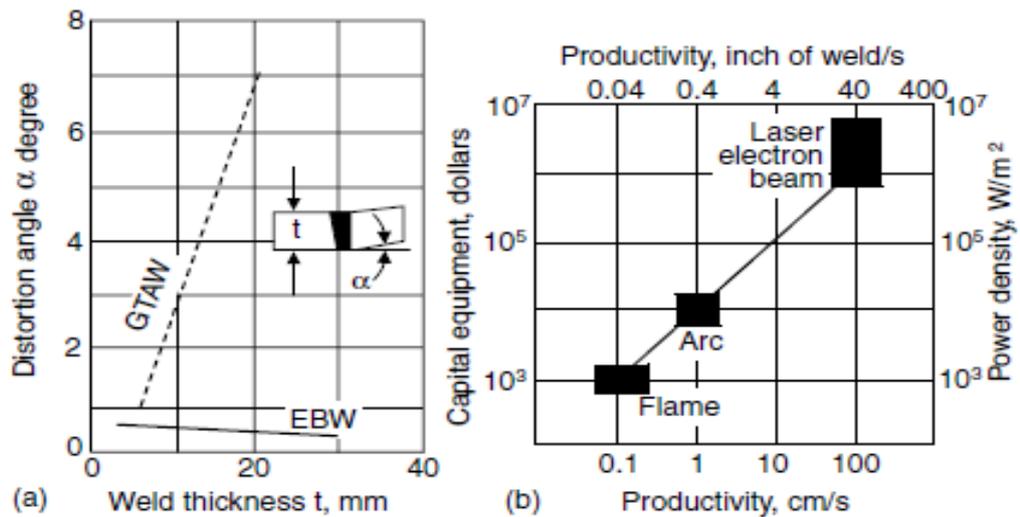


Figure 1.3 Comparisons between welding processes: (a) angular distortion; (b) capital equipment cost. Reprinted from Mendez and Eagar (2).

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Table 1.1 summarizes the fusion welding processes recommended for carbon steels, low-alloy steels, stainless steels, cast irons, nickel-base alloys, and aluminum alloys (3). For one example, GMAW can be used for all the materials of almost all thickness ranges while GTAW is mostly for thinner workpieces. For another example, any arc welding process that requires the use of a flux, such as SMAW, SAW, FCAW, and ESW, is not applicable to aluminum alloys.

Material	Thickness ^b	SMAW	SAW	GMAW	FCAW	GTAW	PAW	ESW	OPW	EBW	LBW
Carbon steels	S	X	X	X		X		X	X	X	X
	I	X	X	X	X	X		X	X	X	X
	M	X	X	X	X			X	X	X	
	T	X	X	X							
Low-alloy steels	S	X	X	X	X	X		X		X	X
	I	X	X	X	X	X				X	X
	M	X	X	X	X			X		X	
	T	X	X	X							
Stainless steels	S	X	X	X	X	X	X		X	X	X
	I	X	X	X	X	X				X	X
	M	X	X	X	X					X	
	T	X	X	X							
Cast iron	I	X							X	X	
	M	X						X	X		
	T	X									
Nickel and alloys	S	X		X		X	X	X		X	X
	I	X		X		X				X	X
	M	X		X						X	
	T	X		X							
Aluminum and alloys	S			X		X	X		X		X
	I			X		X				X	X
	T			X		X					

* Process code: SMAW, shielded metal arc welding; SAW, submerged arc welding; GMAW, gas-metal arc welding; FCAW, gas-tungsten arc welding; GTAW, gas-tungsten arc welding; PAW, plasma arc welding; ESW, electron beam welding; OPW, oxygen beam welding; EBW, electron beam welding; LBW, laser beam welding.

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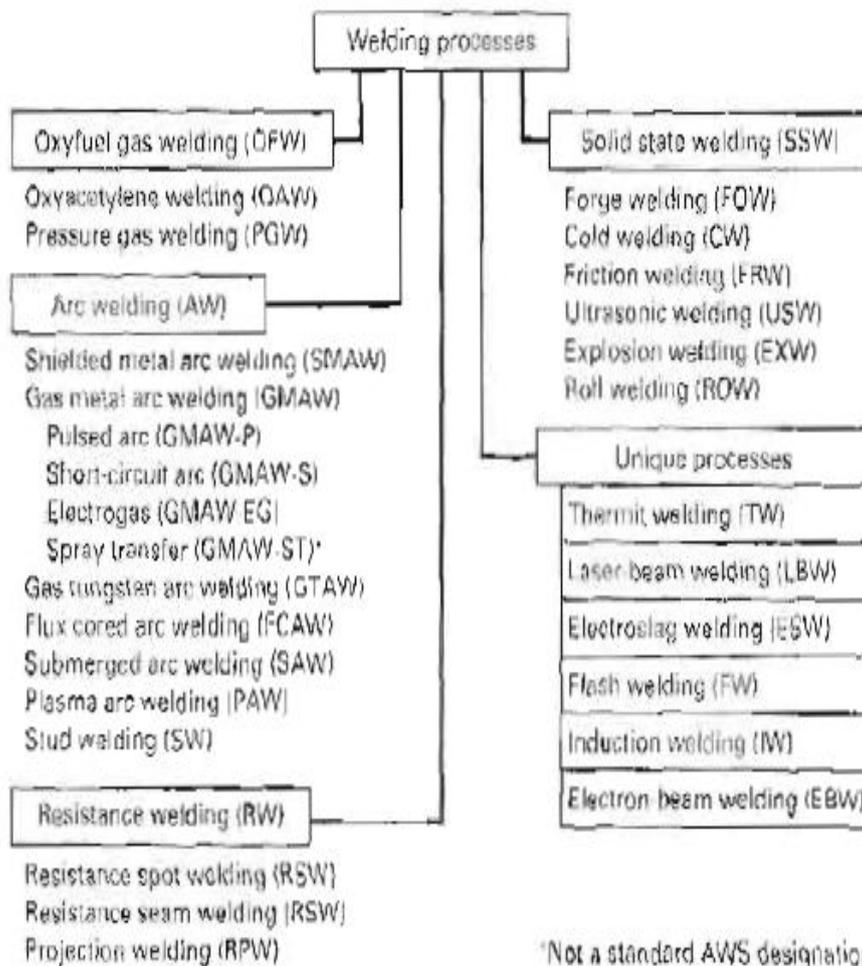


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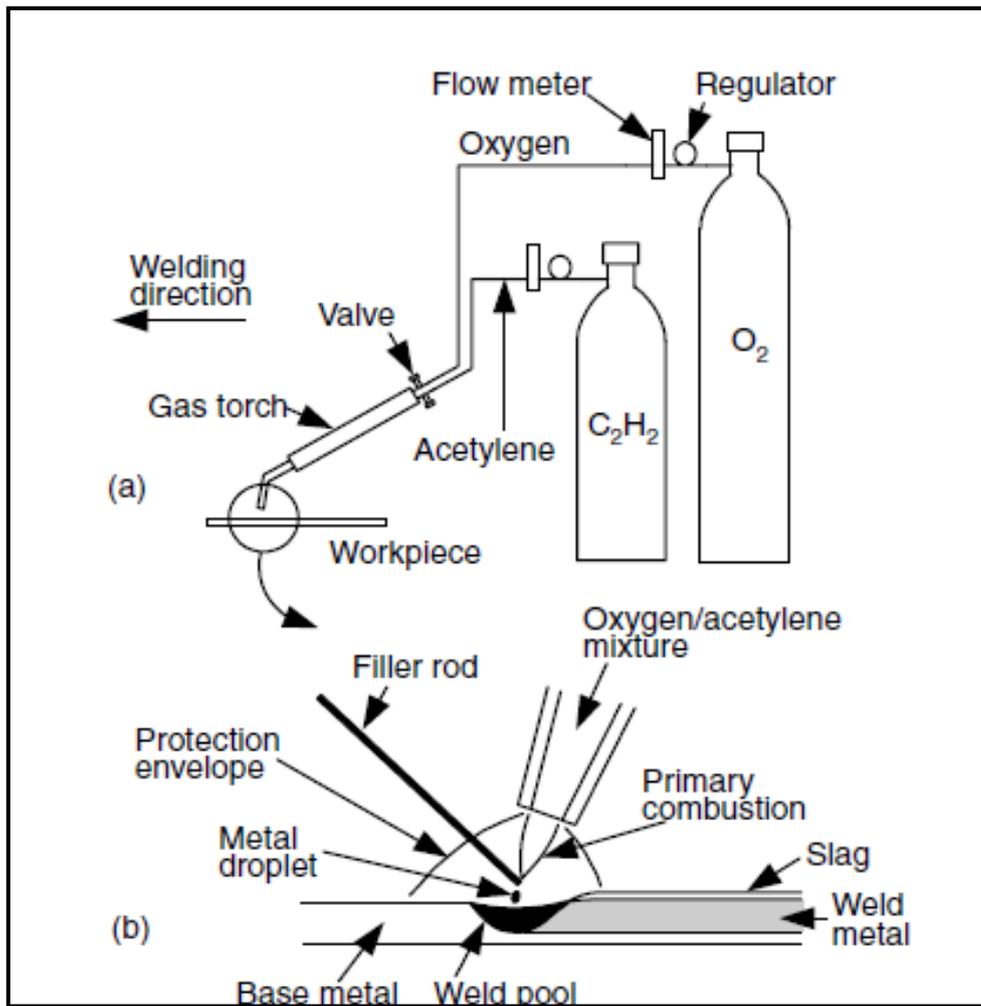


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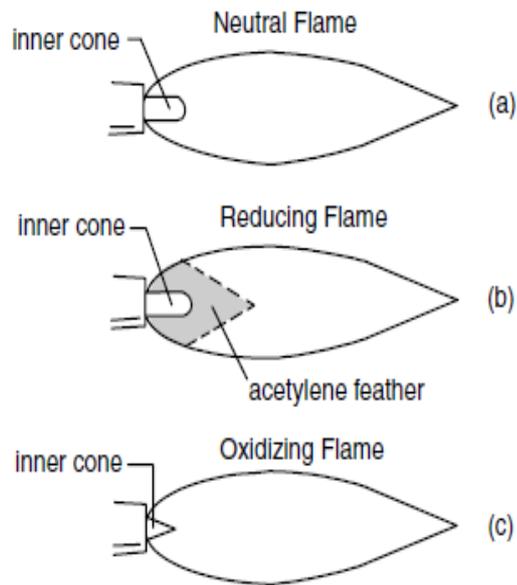


Figure 1.8 Three types of flames in oxyacetylene welding. Modified from *Welding Journal* (4). Courtesy of American Welding Society.

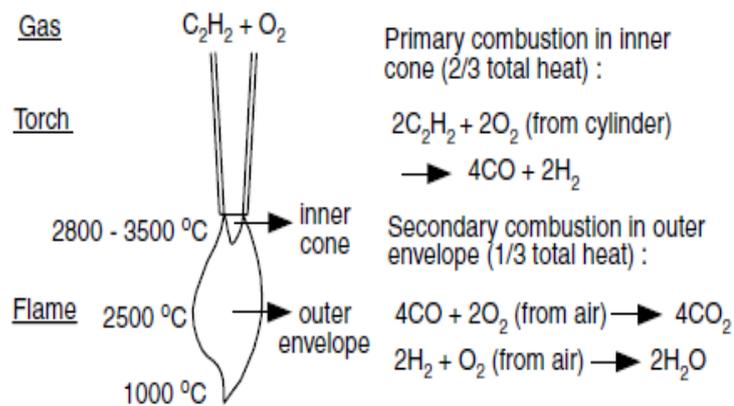


Figure 2.3 Chemical reactions and temperature distribution in a neutral oxyacetylene flame

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3 Electric Arc Welding

Arc welding (AW) is a fusion-welding process in which coalescence of the metals is achieved by the heat of an electric arc between an electrode and the work. The same basic process is also used in arc cutting. A generic AW process is shown in **Figure 3.1**. An electric arc is a discharge of electric current across a gap in a circuit. It is sustained by the presence of a thermally ionized column of gas (called a plasma) through which current flows. To initiate the arc in an AW process, the electrode is brought into contact with the work and then quickly separated from it by a short distance. The electric energy from the arc thus formed produces temperatures of 5500°C or higher, sufficiently hot to melt any metal. A pool of molten metal consisting of base metal(s) and filler metal (if one is used) is formed near the tip of the electrode. In most arc welding processes, filler metal is added during the operation to increase the volume and strength of the weld joint.

As the movement of the electrode relative to the work is accomplished by either a human welder (manual welding) or by mechanical means (i.e., machine welding, automatic welding, or robotic welding). One of the troublesome aspects of manual arc welding is that the quality of the weld joint depends on the skill and work ethic of the human welder. Productivity is also an issue. It is often measured as arc time (also called arc-on time)—the proportion of hours worked that arc welding is being accomplished:

$$\text{Arc time} = (\text{time arc is on}) / (\text{hours worked})$$

This definition can be applied to an individual welder or to a mechanized workstation. For manual welding, arc time is usually around 20%. Frequent rest periods are needed by the welder to overcome fatigue in manual arc welding, which requires hand eye coordination under stressful conditions. Arc time increases to about 50% (more or less, depending on the operation) for machine, automatic, and robotic welding.

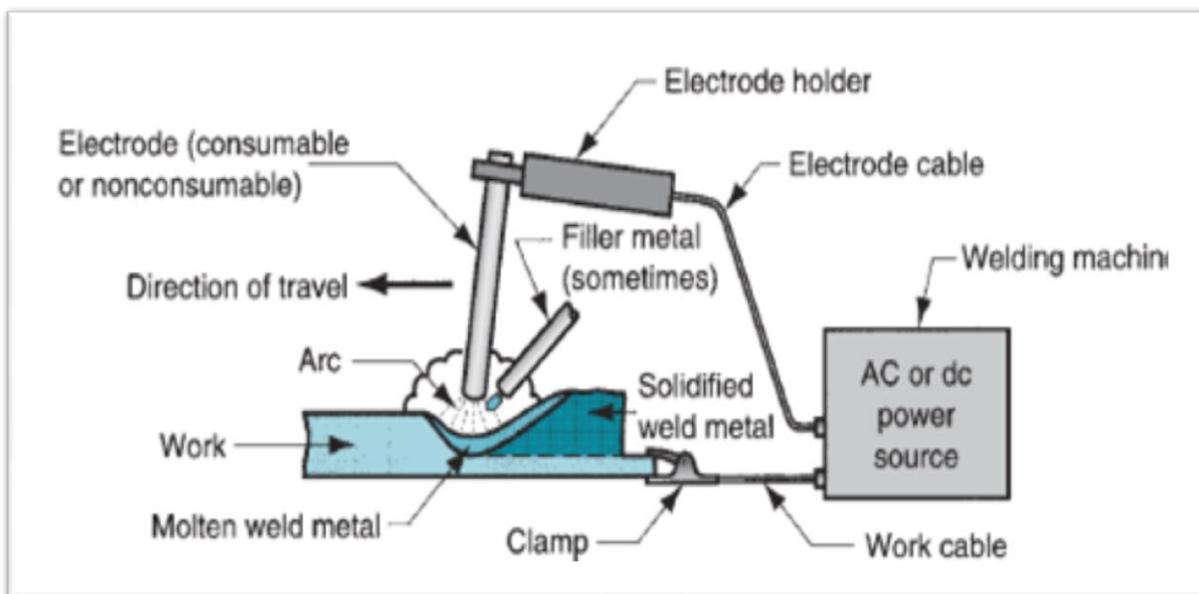


Figure 3.1 The basic configuration and electrical circuit of an arc welding process.

3-1 GENERAL TECHNOLOGY OF ARC WELDING

Before describing the individual AW processes, it is instructional to examine some of the general technical issues that apply to these processes.

Electrodes

Electrodes used in AW processes are classified as consumable or nonconsumable.

Consumable electrodes provide the source of the filler metal in arc welding.

These electrodes are available in two principal forms: rods (also called sticks) and wire. Welding rods are typically 225 to 450 mm (9–18 in) long and 9.5 mm (3/8 in) or less in diameter. The problem with consumable welding rods, at least in production welding operations, is that they must be changed periodically, reducing arc time of the welder. Consumable weld wire has the advantage that it can be continuously fed into the weld pool from spools containing long lengths of wire, thus avoiding the frequent interruptions that occur when using welding sticks. In both rod and wire forms, the electrode is consumed by the arc during the welding process and added to the weld joint as filler metal.

Nonconsumable electrodes are made of tungsten (or carbon, rarely), which resists melting by the arc. Despite its name, a nonconsumable electrode is gradually depleted during the welding process (vaporization is the principal mechanism), analogous to the gradual wearing of a cutting tool in a machining operation. For AW processes that utilize nonconsumable electrodes, any filler metal used in the operation must be supplied by means of a separate wire that is fed into the weld pool.

Arc Shielding

At the high temperatures in arc welding, the metals being joined are chemically reactive to oxygen, nitrogen, and hydrogen in the air. The mechanical properties of the weld joint can be seriously degraded by these reactions. Thus, some means to shield the arc from the surrounding air is provided in nearly all AW processes. Arc shielding is accomplished by covering the electrode tip, arc, and molten weld pool with a blanket of gas or flux, or both, which inhibit exposure of the weld metal to air.

Common shielding gases include argon and helium, both of which are inert. In the welding of ferrous metals with certain AW processes, oxygen and carbon dioxide are used, usually in combination with Ar and/or He, to produce an oxidizing atmosphere or to control weld shape.

A flux is a substance used to prevent the formation of oxides and other unwanted contaminants, or to dissolve them and facilitate removal. During welding, the flux melts and becomes a liquid slag, covering the operation and protecting the molten weld metal. The slag hardens upon cooling and must be removed later by chipping or brushing. Flux is usually formulated to serve several additional functions: (1) provide a protective atmosphere for welding, (2) stabilize the arc, and (3) reduce spattering.

The method of flux application differs for each process. The delivery techniques include (1) pouring granular flux onto the welding operation, (2) using a stick electrode coated with flux material in which the coating melts during welding to cover the operation, and (3) using tubular electrodes in which flux is contained in the core and released as the electrode is consumed. These techniques are discussed further in our descriptions of the individual AW processes.

Power Source in Arc Welding Both direct current (DC) and alternating current (AC)

are used in arc welding. AC machines are less expensive to purchase and operate, but are generally restricted to welding of ferrous metals. DC equipment can be used on all metals with good results and is generally noted for better arc control.

In all arc-welding processes, power to drive the operation is the product of the current I passing through the arc and the voltage E across it. This power is converted into heat, but not all of the heat is transferred to the surface of the work. Convection, conduction, radiation, and spatter account for losses that reduce the amount of usable heat. The effect of the losses is expressed by the heat transfer factor f_1 . Some representative values of f_1 for several AW processes are given in **Table 3.1**.

TABLE 3.1 Heat transfer factors for several arc-welding processes.

Arc-Welding Process ^a	Typical Heat Transfer Factor f_1
Shielded metal arc welding	0.9
Gas metal arc welding	0.9
Flux-cored arc welding	0.9
Submerged arc welding	0.95
Gas tungsten arc welding	0.7

Heat transfer factors are greater for AW processes that use consumable electrodes because most of the heat consumed in melting the electrode is subsequently transferred to the work as molten metal. The process with the lowest f_1 value in Table 3.1 is gas tungsten arc welding, which uses a nonconsumable electrode. Melting factor f_2 further reduces the available heat for welding. The resulting power balance in arc welding is defined by

$$RH_w = f_1 f_2 IE = U_m A_w v \dots\dots\dots 2$$

Where E = voltage, V; I = current, A; and the other terms were defined in Section 29.3. The units of RH_w are watts (current multiplied by voltage), which equal J/sec. This can be converted to Btu/sec by recalling that 1 Btu = 1055 J, and thus 1 Btu/sec = 0.95 watts.

Example 3.1 Power in Arc Welding

A gas tungsten arc-welding operation is performed at a current of 300 A and voltage of 20 V. The melting factor $f_2 = 0.5$, and the unit melting energy for the metal $U_m = 10$ J/mm³. Determine (a) power in the operation, (b) rate of heat generation at the weld, and (c) volume rate of metal welded.

Solution:

(a) The power in this arc-welding operation is

$$P = IE = 300 \times 20 = 6000 \text{ W}$$

(b) From Table 30.1, the heat transfer factor $f_1 = 0.7$. The rate of heat used for welding is given by

$$RH_w = f_1 f_2 IE = 0.7 \times 0.5 \times 6000 = 2100 \text{ W} = 2100 \text{ J/s}$$

(c) The volume rate of metal welded is

$$RVW = 2100 \text{ J/s} = 10 \text{ J/mm}^3 = 210 \text{ mm}^3/\text{s}$$

3-2 ELECTRIC ARC WELDING

Electric Power for Welding

AC current or DC current can be used for arc welding. For most purposes, DC current is preferred. In D.C. welding, a D.C. generator or a solid state rectifier is used. D.C. machines are made up to the capacity range of 600 amperes. The voltage in open circuit is kept around 45 to 95 volts and in closed circuit it is kept 17 to 25 volts. D.C. current can be given in two ways:

- (a) Straight polarity welding.
- (b) Reverse polarity welding.

In straight polarity welding work piece is made anode and the electrode is made cathode as shown in the **Figure 3.2**. Electrons flow from cathode to anode, thus, heat is produced at the materials to be welded.

In reverse polarity system the work is made cathode and the electrode is made anode, as shown in the **Figure 3.3**. This welding is done specially for thin section.

AC welding has the advantage of being cheap. Equipment used is simpler than DC welding. A transformer is used to increase the current output at the electrode. The current varies from 150 to 1000 amperes depending upon the type of work.

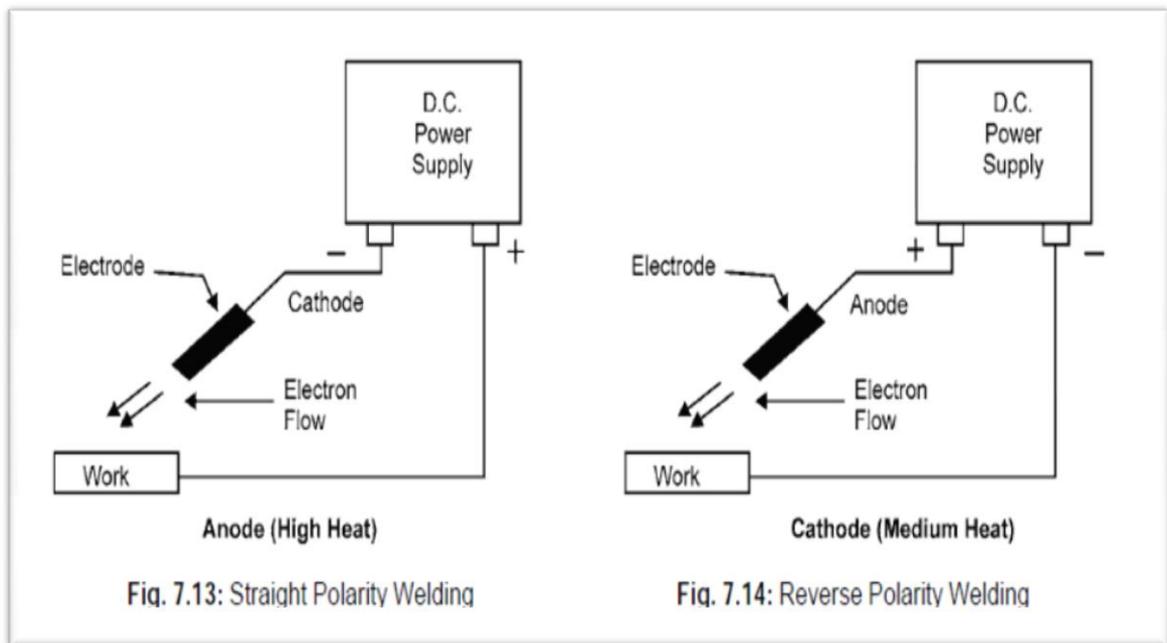


Figure 3.2: Straight Polarity Welding

Figure 3.3: Reverse Polarity Welding

Effect of Arc Length

Arc length is the distance from the tip of the electrode to the bottom of the arc. It should vary from 3 to 4 mm. In short arc length, the time of contact will be shorter and will make a wide and shallow bead. The penetration is low as compared to long arc lengths.

Equipment used for Arc Welding

Various equipments used for arc welding are as under:

1. D.C. Welding Equipment

- (a) AC Motor - Generator set
- (b) Diesel Engine - Generator set

(c) Transformer - Rectifier welding set

2. AC Equipment

(a) Welding transformer set

3. Equipment accessories

(a) Leads

(b) Holder

(c) Connectors

(d) Ground Clamps

4. Operator's tool

(a) Chipping hammer

(b) Wire brush

(c) Arc shield

(d) Closed shoe

The details of the above equipment and accessories are described below:

1.AC Motor Generator:

In this a generator is driven by a suitable AC motor. The average voltage of the generator is 25 volt. The current ranges from 25 to 100 amperes. The voltage in the generator is variable. The voltage can be set to the desired value with the help of rheostat.

2. Diesel Engine Generator Set: In this set, the drive is given by a diesel engine. Rest of the system is same as in case of A.C. motor generator. Diesel engine generator sets are used in the areas when electricity is not available.

3. Transformer Rectifier Set: It allows the current to flow through it only in one direction because it has a one way valve or solid rectifier installed on the electrode side of the secondary coil. The set can supply straight polarity and reverse polarity power supply. The rectifier, are of two types

(a) Silicon diode

(b) Selenium plate

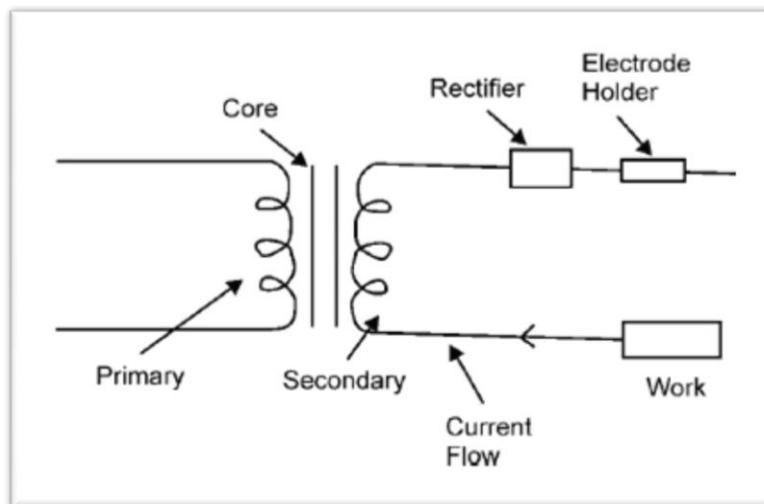


Figure 3.4: Transformer Rectifier Set

4. Welding Transformer Set: It is used to step down the voltage supply. It consists of a primary and secondary circuit. The input is given to primary winding. By electromagnetic induction the current flows through the secondary coil. The output can be controlled as per requirement.

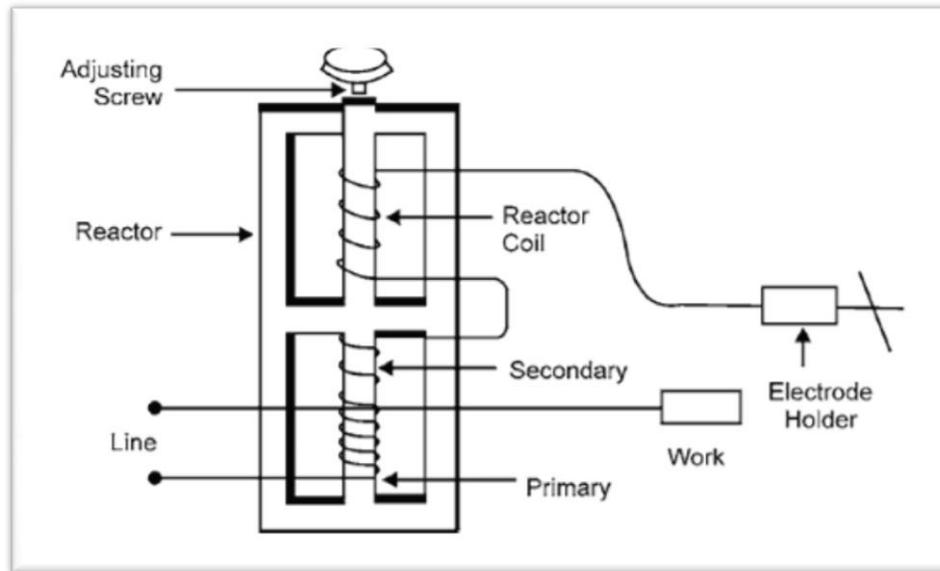


Figure 3.5: Welding Transformer Set

- 5. Cables or Leads:** These leads are made up of copper or aluminum wire. The wires are insulated with rubber & cloth fibre. A heavy insulation is necessary for these cables.
- 6. Face Shield:** When arc is produced around the job, infrared rays and ultraviolet rays are produced. To protect the face and eyes from these dangerous rays, a shield is necessary.
- 7. Other Accessories & Tools:** Other accessories & tools used for arc welding are shown in the **Figure 3.6**.

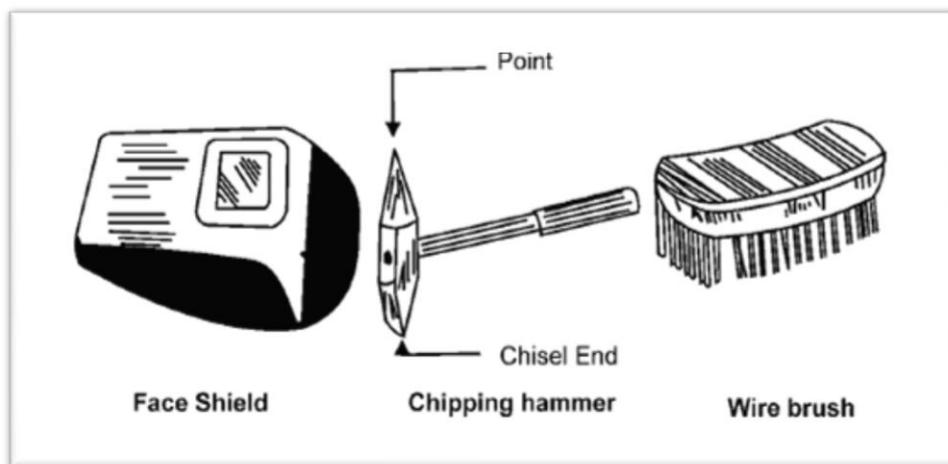


Figure 3.6: Other Accessories

Welding Positions

In horizontal position it is very easy to weld. But many times it is impossible to weld the job in horizontal position. Other positions are classified as under:

- (a) Flat Position
- (b) Horizontal Position
- (c) Vertical Position
- (d) Overhead Position

1. Flat Position: In flat positions the work piece is kept in nearly horizontal position. The surface to be worked is kept on upper side. The welding is done as illustrated in the **Figure 3.7**

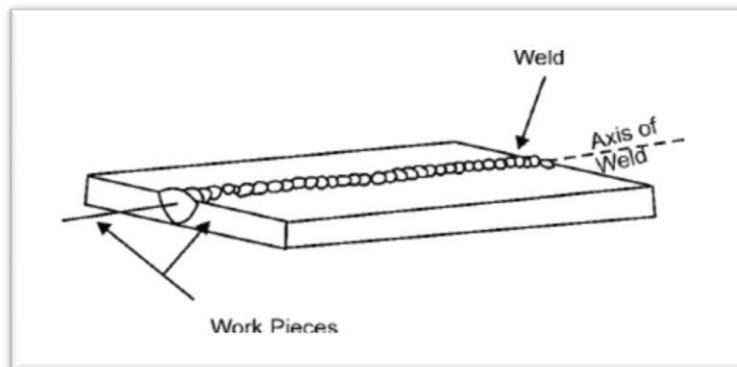


Figure 3.7: Flat Position

2. Horizontal Position: In this position, the work piece is kept as in the **Figure 3.8** . Two surfaces rest one over the other with their flat faces in vertical plane. Welding is done from right side to left side. The axis of the weld is in a horizontal plane and its face in vertical plane.

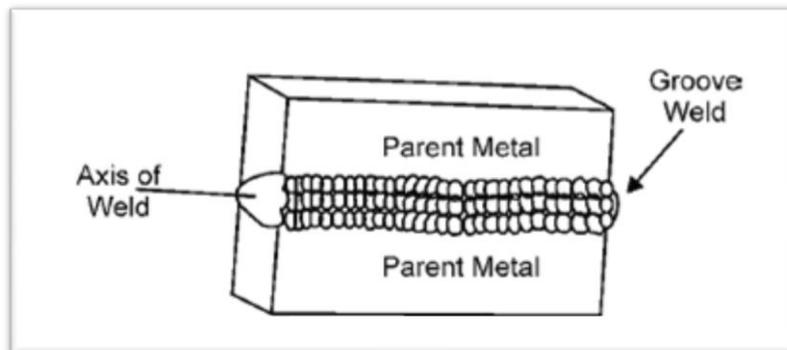


Figure 3.8 : Horizontal Position

3. Vertical Position: In this position, the axis of the weld remains in approximate vertical plane. The welding is started at the bottom and proceeds towards top. Welding process is illustrated in **Figure 3.9** .

4. Overhead Position: As shown in the figure, the work piece remains over the head of the welder. The work piece and the axis of the weld remain approximate in horizontal plane. It is the most difficult position of welding. Welding process is illustrated in **Figure 3.10** .

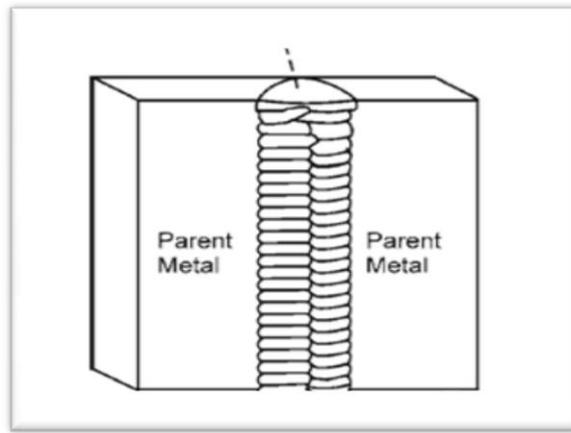


Figure 3.9: Vertical Position

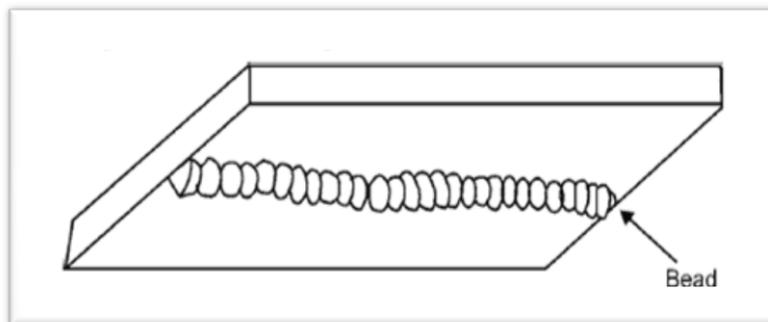


Figure 3.10 : Overhead Position

Types of Electrodes

Electrodes are of two types

1. Coated electrodes: Coated electrodes are generally applied in arc welding processes. A metallic core is coated with some suitable material. The material used for core is mild steel, nickel steel, chromium molybdenum steel, etc. One end of the coated core is kept bare for holding.

2. Bare electrodes: Bare electrodes produce the welding of poor quality. These are cheaper than coated electrodes. These are generally used in modern welding process like MIG welding.

Electrode Size

Electrodes are commonly made in lengths 250 mm, 300 mm, 350 mm, 450 mm, and the diameters are 1.6 mm, 2 mm, 2.5 mm, 3.2 mm, 4 mm, 7 mm, 8 mm and 9 mm.

Functions of Coatings

The coating on an electrode serves the following functions:

1. To prevent oxidation.
2. Forms slags with metal impurities.
3. It stabilizes the arc.
4. Increases deposition of molten metal.
5. Controls depth of penetration.
6. Controls the cooling rate.
7. Adds alloy elements to the joint. Specifications of electrodes.

COMPARISON BETWEEN AC AND DC WELDING

7.6 COMPARISON BETWEEN AC AND DC WELDING

<i>S.No.</i>	<i>A.C. welding</i>	<i>D.C. welding</i>
1.	Equipment is cheaper and simpler in operation.	1. Equipment is costlier and complicated in operation.
2.	In AC transformer there is no moving part, therefore it is easy to maintain.	2. DC generator set has many moving parts and its maintenance cost is higher than AC transformers.
3.	It can be operated at large distances from power sources as the voltage drop is negligible.	3. In DC the voltage drop is very high. Therefore, shorter cables are used.
4.	Only coated electrodes can be used in AC welding.	4. Both coated and bare electrodes can be used.
5.	Less problem of arc blow.	5. More problem of arc blow.
6.	It can not be used for welding non-ferrous metals	6. Almost all the metals can be welded.
7.	It can be used only when AC current is available	7. An engine generator can be used in case of non-availability of AC power.

3 Electric Arc Welding

Arc welding (AW) is a fusion-welding process in which coalescence of the metals is achieved by the heat of an electric arc between an electrode and the work. The same basic process is also used in arc cutting. A generic AW process is shown in **Figure 3.1**. An electric arc is a discharge of electric current across a gap in a circuit. It is sustained by the presence of a thermally ionized column of gas (called a plasma) through which current flows. To initiate the arc in an AW process, the electrode is brought into contact with the work and then quickly separated from it by a short distance. The electric energy from the arc thus formed produces temperatures of 5500°C or higher, sufficiently hot to melt any metal. A pool of molten metal consisting of base metal(s) and filler metal (if one is used) is formed near the tip of the electrode. In most arc welding processes, filler metal is added during the operation to increase the volume and strength of the weld joint.

As the movement of the electrode relative to the work is accomplished by either a human welder (manual welding) or by mechanical means (i.e., machine welding, automatic welding, or robotic welding). One of the troublesome aspects of manual arc welding is that the quality of the weld joint depends on the skill and work ethic of the human welder. Productivity is also an issue. It is often measured as arc time (also called arc-on time)—the proportion of hours worked that arc welding is being accomplished:

$$\text{Arc time} = (\text{time arc is on}) / (\text{hours worked})$$

This definition can be applied to an individual welder or to a mechanized workstation. For manual welding, arc time is usually around 20%. Frequent rest periods are needed by the welder to overcome fatigue in manual arc welding, which requires hand eye coordination under stressful conditions. Arc time increases to about 50% (more or less, depending on the operation) for machine, automatic, and robotic welding.

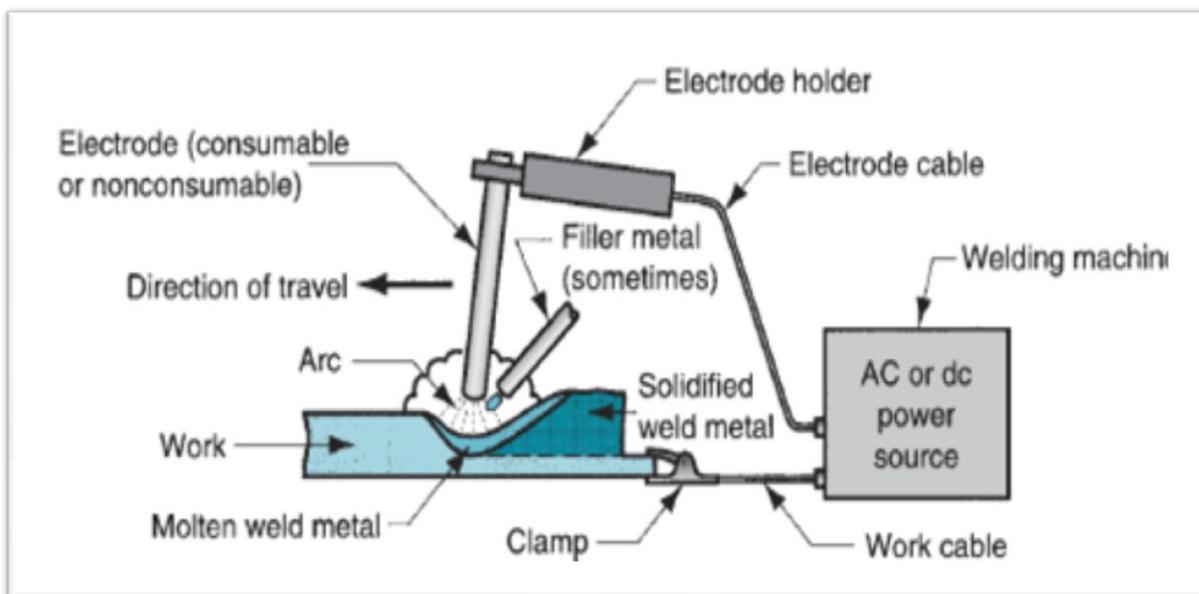


Figure 3.1 The basic configuration and electrical circuit of an arc welding process.

3-1 GENERAL TECHNOLOGY OF ARC WELDING

Before describing the individual AW processes, it is instructional to examine some of the general technical issues that apply to these processes.

Electrodes

Electrodes used in AW processes are classified as consumable or nonconsumable.

Consumable electrodes provide the source of the filler metal in arc welding.

These electrodes are available in two principal forms: rods (also called sticks) and wire. Welding rods are typically 225 to 450 mm (9–18 in) long and 9.5 mm (3/8 in) or less in diameter. The problem with consumable welding rods, at least in production welding operations, is that they must be changed periodically, reducing arc time of the welder. Consumable weld wire has the advantage that it can be continuously fed into the weld pool from spools containing long lengths of wire, thus avoiding the frequent interruptions that occur when using welding sticks. In both rod and wire forms, the electrode is consumed by the arc during the welding process and added to the weld joint as filler metal.

Nonconsumable electrodes are made of tungsten (or carbon, rarely), which resists melting by the arc. Despite its name, a nonconsumable electrode is gradually depleted during the welding process (vaporization is the principal mechanism), analogous to the gradual wearing of a cutting tool in a machining operation. For AW processes that utilize nonconsumable electrodes, any filler metal used in the operation must be supplied by means of a separate wire that is fed into the weld pool.

Arc Shielding

At the high temperatures in arc welding, the metals being joined are chemically reactive to oxygen, nitrogen, and hydrogen in the air. The mechanical properties of the weld joint can be seriously degraded by these reactions. Thus, some means to shield the arc from the surrounding air is provided in nearly all AW processes. Arc shielding is accomplished by covering the electrode tip, arc, and molten weld pool with a blanket of gas or flux, or both, which inhibit exposure of the weld metal to air.

Common shielding gases include argon and helium, both of which are inert. In the welding of ferrous metals with certain AW processes, oxygen and carbon dioxide are used, usually in combination with Ar and/or He, to produce an oxidizing atmosphere or to control weld shape.

A flux is a substance used to prevent the formation of oxides and other unwanted contaminants, or to dissolve them and facilitate removal. During welding, the flux melts and becomes a liquid slag, covering the operation and protecting the molten weld metal. The slag hardens upon cooling and must be removed later by chipping or brushing. Flux is usually formulated to serve several additional functions: (1) provide a protective atmosphere for welding, (2) stabilize the arc, and (3) reduce spattering.

The method of flux application differs for each process. The delivery techniques include (1) pouring granular flux onto the welding operation, (2) using a stick electrode coated with flux material in which the coating melts during welding to cover the operation, and (3) using tubular electrodes in which flux is contained in the core and released as the electrode is consumed. These techniques are discussed further in our descriptions of the individual AW processes.

Power Source in Arc Welding Both direct current (DC) and alternating current (AC)

are used in arc welding. AC machines are less expensive to purchase and operate, but are generally restricted to welding of ferrous metals. DC equipment can be used on all metals with good results and is generally noted for better arc control.

In all arc-welding processes, power to drive the operation is the product of the current I passing through the arc and the voltage E across it. This power is converted into heat, but not all of the heat is transferred to the surface of the work. Convection, conduction, radiation, and spatter account for losses that reduce the amount of usable heat. The effect of the losses is expressed by the heat transfer factor f_1 . Some representative values of f_1 for several AW processes are given in **Table 3.1**.

TABLE 3.1 Heat transfer factors for several arc-welding processes.

Arc-Welding Process ^a	Typical Heat Transfer Factor f_1
Shielded metal arc welding	0.9
Gas metal arc welding	0.9
Flux-cored arc welding	0.9
Submerged arc welding	0.95
Gas tungsten arc welding	0.7

Heat transfer factors are greater for AW processes that use consumable electrodes because most of the heat consumed in melting the electrode is subsequently transferred to the work as molten metal. The process with the lowest f_1 value in Table 30.1 is gas tungsten arc welding, which uses a nonconsumable electrode. Melting factor f_2 further reduces the available heat for welding. The resulting power balance in arc welding is defined by

$$RH_w = f_1 f_2 IE = U_m A_w v \dots\dots\dots 2$$

Where E = voltage, V; I = current, A; and the other terms were defined in Section 29.3. The units of RH_w are watts (current multiplied by voltage), which equal J/sec. This can be converted to Btu/sec by recalling that 1 Btu = 1055 J, and thus 1 Btu/sec = 0.95 watts.

Example 3.1 Power in Arc Welding

A gas tungsten arc-welding operation is performed at a current of 300 A and voltage of 20 V. The melting factor $f_2 \approx 0.5$, and the unit melting energy for the metal $U_m \approx 10$ J/mm³. Determine (a) power in the operation, (b) rate of heat generation at the weld, and (c) volume rate of metal welded.

Solution:

(a) The power in this arc-welding operation is

$$P = IE = 300 \times 20 = 6000 \text{ W}$$

(b) From Table 30.1, the heat transfer factor $f_1 = 0.7$. The rate of heat used for welding is given by

$$RH_w = f_1 f_2 IE = 0.7 \times 0.5 \times 6000 = 2100 \text{ W} = 2100 \text{ J/s}$$

(c) The volume rate of metal welded is

$$RVW = 2100 \text{ J/s} = 10 \text{ J/mm}^3 = 210 \text{ mm}^3/\text{s}$$

FUNDAMENTALS OF WELDING

1- INTRODUCTION

The *term joining* is generally used for welding, brazing, soldering, and adhesive bonding, which form a permanent joint between the parts—a joint that cannot easily be separated. The term assembly usually refers to mechanical methods of fastening parts together. Some of these methods allow for easy disassembly, while others do not.

We begin our coverage of the joining and assembly processes with welding,

Welding is a materials joining process in which two or more parts are coalesced at their contacting surfaces by a suitable application of heat and/or pressure. Many welding processes are accomplished by heat alone, with no pressure applied; others by a combination of heat and pressure; and still others by pressure alone, with no external heat supplied. In some welding processes a filler material is added to facilitate coalescence. The assemblage of parts that are joined by welding is called a *weldment*.

Welding is most commonly associated with metal parts, but the process is also used for joining plastics. Our discussion of welding will focus on metals. Welding is a relatively new process (Historical Note 29.1). Its commercial and technological importance derives from the following:

- 1- Welding provides a permanent joint. The welded parts become a single entity.
- 2- The welded joint can be stronger than the parent materials if a filler metal is used that has strength properties superior to those of the parents, and if proper welding techniques are used.
- 3- Welding is usually the most economical way to join components in terms of material usage and fabrication costs. Alternative mechanical methods of assembly require more complex shape alterations (e.g., drilling of holes) and addition of fasteners (e.g., rivets or bolts). The resulting mechanical assembly is usually heavier than a corresponding weldment.
- 4- Welding is not restricted to the factory environment. It can be accomplished “in the field.”

Although welding has the advantages indicated above, it also has certain limitations and drawbacks (or potential drawbacks):

- 1- Most welding operations are performed manually and are expensive in terms of labor cost. Many welding operations are considered “skilled trades,” and the labor to perform these operations may be scarce.
- 2- Most welding processes are inherently dangerous because they involve the use of high energy.
- 3- Since welding accomplishes a permanent bond between the components, it does not allow for convenient disassembly. If the product must occasionally be disassembled (e.g., for repair or maintenance), then welding should not be used as the assembly method.
- 4- The welded joint can suffer from certain quality defects that are difficult to detect. The defects can reduce the strength of the joint.

Welding involves localized coalescence or joining together of two metallic parts at their faying surfaces. The faying surfaces are the part surfaces in contact or close proximity that are to be joined. Welding is usually performed on parts made of the same metal, but some welding operations can be used to join dissimilar metals.

2- TYPES OF WELDING PROCESSES

Some 50 different types of welding operations have been cataloged by the American Welding Society. They use various types or combinations of energy to provide the required power. We can divide the welding processes into two major groups: (1) fusion welding and (2) solid-state welding.

1-Fusion Welding

Fusion-welding processes use heat to melt the base metals. In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and strength to the

welded joint. A fusion-welding operation in which no filler metal is added is referred to as an autogenous weld. The fusion category includes the most widely used welding processes, which can be organized into the following general groups (initials in parentheses are designations of the American Welding Society):

Arc welding (AW). Arc welding refers to a group of welding processes in which heating of the metals is accomplished by an electric arc, as shown in **Figure 1**. Some arc welding operations also apply pressure during the process and most utilize a filler metal.

Resistance welding (RW). Resistance welding achieves coalescence using heat from electrical resistance to the flow of a current passing between the faying surfaces of two parts held together under pressure. included spot welding and seam welding, two joining methods widely used today in sheet metal working.

Oxyfuel gas welding (OFW). These joining processes use an oxyfuel gas, such as a mixture of oxygen and acetylene, to produce a hot flame for melting the base metal and filler metal, if one is used. Although Davy discovered acetylene gas early in the 1800s, oxyfuel gas welding required the subsequent development of torches for combining acetylene and oxygen around 1900. During the 1890s, hydrogen and natural gas were mixed with oxygen for welding, but the oxyacetylene flame achieved significantly higher temperatures. These three welding processes—arc welding, resistance welding, and oxyfuel gas welding—constitute by far the majority of welding operations performed today.

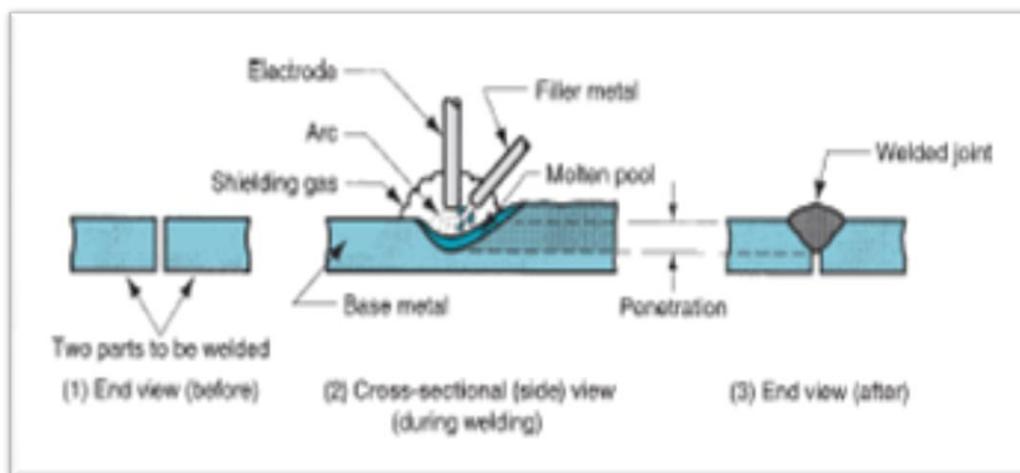


Figure 1 Basics of arc welding: (1) before the weld; (2) during the weld (the base metal is melted and filler metal is added to the molten pool); and (3) the completed weldment.

There are many variations of the arc-welding process.

Other fusion-welding processes. Other welding processes that produce fusion of the metals joined include electron beam welding and laser beam welding. Certain arc and oxyfuel processes are also used for cutting metals.

2- Solid-State Welding

Solid-state welding refers to joining processes in which coalescence results from application of pressure alone or a combination of heat and pressure. If heat is used, the temperature in the process is below the melting point of the metals being welded. No filler metal is utilized. Representative welding processes in this group include:

Diffusion welding (DFW). Two surfaces are held together under pressure at an elevated temperature and the parts coalesce by solid-state diffusion.

Friction welding (FRW). Coalescence is achieved by the heat of friction between two surfaces.

Ultrasonic welding (USW). Moderate pressure is applied between the two parts and an oscillating motion at ultrasonic frequencies is used in a direction parallel to the contacting surfaces. The combination of normal and vibratory forces results in shear stresses that remove surface films and achieve atomic bonding of the surfaces.

3- WELDING AS A COMMERCIAL OPERATION

The principal applications of welding are (1) construction, such as buildings and bridges; (2) piping, pressure vessels, boilers, and storage tanks; (3) shipbuilding; (4) aircraft and aerospace; and (5) automotive and railroad .

Welding is performed in a variety of locations and in a variety of industries. Owing to its versatility as an assembly technique for commercial products, many welding operations are performed in factories. However, several of the traditional processes, such as arc welding and oxyfuel gas welding, use equipment that can be readily moved, so these operations are not limited to the factory. They can be performed at construction sites, in shipyards, at customers' plants, and in automotive repair shops.

Most welding operations are labor intensive. For example, arc welding is usually performed by a skilled worker, *called a welder*, who manually controls the path or placement of the weld to join individual parts into a larger unit. In factory operations in which arc welding is manually performed, the welder often works with a second worker, called a *fitter*.

It is the fitter's job to arrange the individual components for the welder prior to making the weld. Welding fixtures and positioners are used for this purpose.

A *welding fixture* is a device for clamping and holding the components in fixed position for welding. It is custom fabricated for the particular geometry of the weldment and therefore must be economically justified on the basis of the quantities of assemblies to be produced.

A *welding positioner* is a device that holds the parts and also moves the assemblage to the desired position for welding. This differs from a welding fixture that only holds the parts in a single fixed position. The desired position is usually one in which the weld path is flat and horizontal.

The Safety Issue Welding is inherently dangerous to human workers. Strict safety precautions must be practiced by those who perform these operations. The high temperatures of the molten metals in welding are an obvious danger. In gas welding, the fuels (e.g., acetylene) are a fire hazard. Most of the processes use high energy to cause melting of the part surfaces to be joined. In many welding processes, electrical power is the source of thermal energy, so there is the hazard of electrical shock to the worker. Certain welding processes have their own particular perils.

In arc welding, for example, ultraviolet radiation is emitted that is injurious to human vision. A special helmet that includes a dark viewing window must be worn by the welder. This window filters out the dangerous radiation but is so dark that it renders the welder virtually blind, except when the arc is struck. Sparks, spatters of molten metal, smoke, and fumes add to the risks associated with welding operations. Ventilation facilities must be used to exhaust the dangerous fumes generated by some of the fluxes and molten metals used in welding. If the operation is performed in an enclosed area, special ventilation suits or hoods are required.

Automation in Welding Because of the hazards of manual welding, and in efforts to increase productivity and improve product quality, various forms of mechanization and automation have been developed.

The categories include machine welding, **automatic welding, and robotic welding.**

Machine welding can be defined as mechanized welding with equipment that performs the operation under the continuous supervision of an operator. It is normally accomplished by a welding head that is moved by mechanical means relative to a stationary work, or by moving the work relative to a stationary welding head. The human worker must continually observe and interact with the equipment to control the operation.

If the equipment is capable of performing the operation without control by a human operator, it is referred to as automatic welding. A human worker is usually present to oversee the process and detect variations from normal conditions. What distinguishes automatic welding from machine welding is a weld cycle controller to regulate the arc movement and workpiece positioning without continuous human attention. Automatic welding requires a welding fixture and/or positioner to position the work relative to the welding head. It also requires a higher degree of consistency and accuracy in the component parts used in the weldment. For these reasons, automatic welding can be justified only for large quantity production.

In robotic welding, an industrial robot or programmable manipulator is used to automatically control the movement of the welding head relative to the work. The versatile reach of the robot arm permits the use of relatively simple fixtures, and the robot's capacity to be reprogrammed for new part configurations allows this form of automation to be justified for relatively low production quantities. A typical robotic arc welding cell consists of two welding fixtures and a human fitter to load and unload parts while the robot welds. In addition to arc welding, industrial robots are also used in automobile final assembly plants to perform resistance welding on car bodies.

Welding produces a solid connection between two pieces, called a weld joint.

A **weld joint** is the junction of the edges or surfaces of parts that have been joined by welding. This section covers two classifications related to weld joints: (1) types of joints and (2) the types of welds used to join the pieces that form the joints.

4- TYPES OF JOINTS

There are five basic types of joints for bringing two parts together for joining. The five joint types are not limited to welding; they apply to other joining and fastening techniques as well.

With reference to **Figure 2**, the five joint types can be defined as follows:

(a) **Butt joint**. In this joint type, the parts lie in the same plane and are joined at their edges.

(b) **Corner joint**. The parts in a corner joint form a right angle and are joined at the corner of the angle.

(c) **Lap joint**. This joint consists of two overlapping parts.

(d) **Tee joint**. In a tee joint, one part is perpendicular to the other in the approximate shape of the letter "T."

(e) **Edge joint**. The parts in an edge joint are parallel with at least one of their edges in common, and the joint is made at the common edge(s).

5- TYPES OF WELDS

Each of the preceding joints can be made by welding. It is appropriate to distinguish between the joint type and the way in which it is welded—the weld type. Differences among weld types are in geometry (joint type) and welding process.

A **fillet weld** is used to fill in the edges of plates created by corner, lap, and tee joints, as in **Figure 3**. Filler metal is used to provide a cross section approximately the shape of a right triangle. It is the most common weld type in arc and oxyfuel welding because it requires minimum edge preparation—the basic square edges of the parts are used. Fillet welds can be single or double (i.e., welded on one side or both) and can be continuous or intermittent (i.e., welded along the entire length of the joint or with unwelded spaces along the length). Groove welds usually require that the edges of the parts be shaped into a groove to facilitate weld penetration. The grooved shapes include square, bevel, V, U, and J, in **Figure 2** Five basic types of joints: (a) butt, (b) corner, (c) lap, (d) tee, and (e) edge.

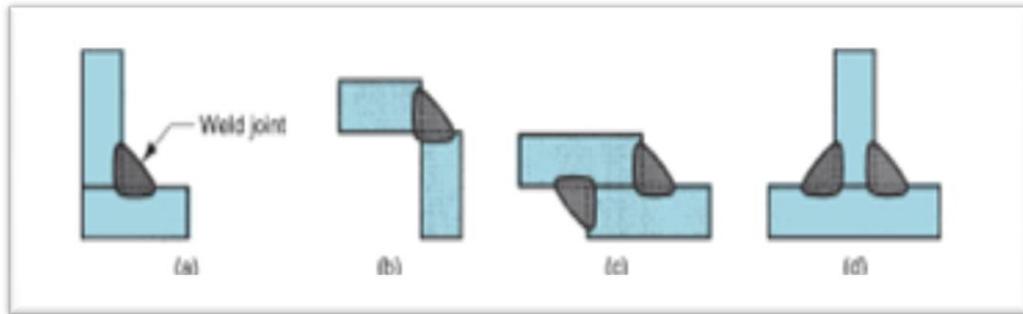
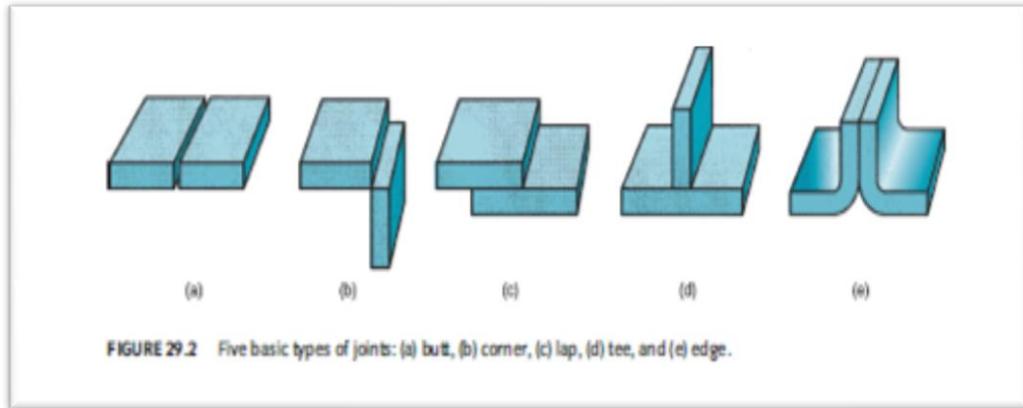


Figure 3 Various forms of fillet welds: (a) inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; and (d) double fillet tee joint. Dashed lines show the original part edges.

Single or double sides, as shown in **Figure 4**. Filler metal is used to fill in the joint, usually by arc or oxyfuel welding. Preparation of the part edges beyond the basic square edge, although requiring additional processing, is often done to increase the strength of the welded joint or where thicker parts are to be welded. Although most closely associated with a butt joint, groove welds are used on all joint types except lap.

Plug welds and slot welds are used for attaching flat plates, as shown in **Figure 5**, using one or more holes or slots in the top part and then filling with filler metal to fuse the two parts together.

Spot welds and seam welds, used for lap joints, are diagrammed in **Figure 6**. A spot weld is a small fused section between the surfaces of two sheets or plates. Multiple spot welds are typically required to join the parts. It is most closely associated with resistance welding. A seam weld is similar to a spot weld except it consists of a more or less continuously fused section between the two sheets or plates.

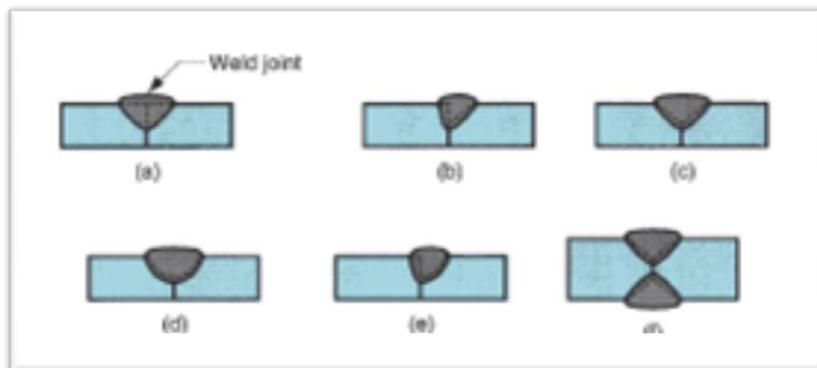


Figure 4 Some typical groove welds (a) square groove weld, one side; (b) single bevel groove weld; (c) single V-groove weld; (d) single U-groove weld; (e) single J-groove weld; (f) double V-groove weld for thicker sections. Dashed lines show the original part edges.

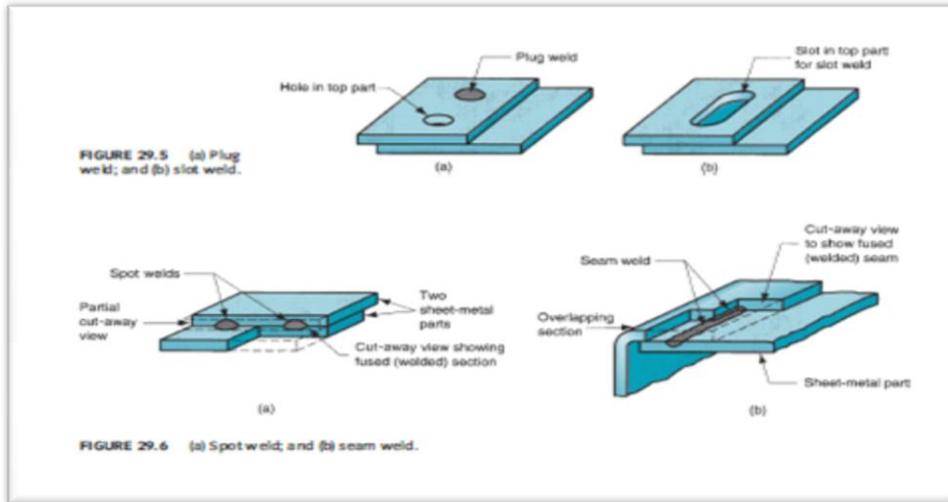


Figure 5 (a) Plug weld; and (b) slot weld. **Figure 6** a) Spot weld; and (b) seam weld.

Flange welds and surfacing welds are shown in **Figure 7**. A flange weld is made on the edges of two (or more) parts, usually sheet metal or thin plate, at least one of the parts being flanged as in **Figure 7** (a). A surfacing weld is not used to join parts, but rather to deposit filler metal onto the surface of a base part in one or more weld beads. The weld beads can be made in a series of overlapping parallel passes, thereby covering large areas of the base part. The purpose is to increase the thickness of the plate or to provide a protective coating on the surface.

Although several coalescing mechanisms are available for welding, fusion is by far the most common means. In this section, we consider the physical relationships that allow fusion welding to be performed. We first examine the issue of power density and its importance, and then we define the heat and power equations that describe a welding process.

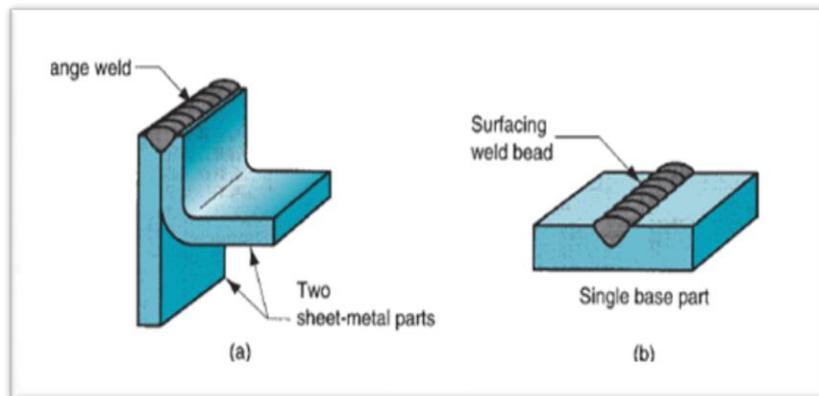


Figure 7 (a) Flange welds and (b) surfacing welds

6- POWER DENSITY

To accomplish fusion, a source of high-density heat energy is supplied to the faying surfaces, and the resulting temperatures are sufficient to cause localized melting of the base metals. If a filler metal is added, the heat density must be high enough to melt it also. Heat density can be defined as the power transferred to the work per unit surface area, W/mm^2 ($Btu/sec-in^2$). The time to melt the metal is inversely proportional to the power density. At low power densities, a significant amount of time is required to cause melting. If power density is too low, the heat is conducted into the work as rapidly as it is added at the surface, and melting never occurs. It has been found that the minimum power density required to melt most metals in welding is about $10 W/mm^2$ ($6 Btu/sec-in^2$). As heat density increases, melting time is reduced. If power density is too high—above around $105 W/mm^2$ ($60,000 Btu/sec-in^2$)—the localized temperatures vaporize the metal in the affected region. Thus,

there is a practical range of values for power density within which welding can be performed. Differences among welding processes in this range are (1) the rate at which welding can be performed and/or (2) the size of the region that can be welded.

Table 1 provides a comparison of power densities for the major fusion welding processes. Oxyfuel gas welding is capable of developing large amounts of heat, but the heat density is relatively low because it is spread over a large area. Oxyacetylene gas, the hottest of the OFW fuels, burns at a top temperature of around 3500_C (6300_F). By comparison, arc welding produces high energy over a smaller area, resulting in local temperatures of 5500_C to 6600_C (10,000_F–12,000_F). For metallurgical reasons, it is desirable to melt the metal with minimum energy, and high power densities are generally preferable.

Welding Process	Approximate Power Density	
	W/mm ²	Btu/sec-in ²
Oxyfuel welding	10	6
Arc welding	50	30
Resistanc welding	1000	600
Laser beam welding	9000	5000
Electron beam welding	10,000	6000

Power density can be computed as the power entering the surface divided by the corresponding surface area:

$$PD = P / A \dots\dots\dots(1)$$

where

PD = power density, W/mm² (Btu/sec-in²); P = power entering the surface, W(Btu/sec); and A= surface area over which the energy is entering,mm² (in²). The issue is more complicated than indicated by Eq. (29.1). One complication is that the power source (e.g., the arc) is moving in many welding processes, which results in preheating ahead of the operation and post heating behind it. Another complication is that power density is not uniform throughout the affected surface; it is distributed as a function of area.

7- HEAT BALANCE IN FUSION WELDING

The quantity of heat required to melt a given volume of metal depends on (1) the heat to raise the temperature of the solid metal to its melting point, which depends on the metal's volumetric specific heat, (2) the melting point of the metal, and (3) the heat to transform the metal from solid to liquid phase at the melting point, which depends on the metal's heat of fusion. To a reasonable approximation, this quantity of heat can be estimated by

$$Um = KT^2 m \dots\dots\dots(2)$$

where Um= the unit energy for melting (i.e., the quantity of heat required to melt a unit volume of metal starting from room temperature), J/mm³ (Btu/in³); Tm ¼ melting point of the metal on an absolute temperature scale, °K(°R); and K = constant whose value is 3.33x10⁻⁶ when the Kelvin scale is used (and K=1.467x10⁻⁵ for the Rankine temperature scale). Absolute melting temperatures for selected metals are presented in **Table 2**.

Table 2 Melting temperatures on the absolute temperature scale for selected metals.

TABLE 29.2 Melting temperatures on the absolute temperature scale for selected metals.					
Metal	Melting Temperature		Metal	Melting Temperature	
	$^{\circ}\text{K}^{\text{a}}$	$^{\circ}\text{R}^{\text{b}}$		$^{\circ}\text{K}^{\text{a}}$	$^{\circ}\text{R}^{\text{b}}$
Aluminum alloys	930	1680	Steels		
Cast iron	1530	2760	Low carbon	1760	3160
Copper and alloys			Medium carbon	1700	3060
Pure	1350	2440	High carbon	1650	2960
Brass, navy	1160	2090	Low alloy	1700	3060
Bronze (90 Cu-10 Sn)	1120	2010	Stainless steels		
Inconel	1660	3000	Austenitic	1670	3010
Magnesium	940	1700	Martensitic	1700	3060
Nickel	1720	3110	Titanium	2070	3730

Based on values in [2].
^aKelvin scale = Centigrade (Celsius) temperature + 273.
^bRankine scale = Fahrenheit temperature + 460.

Not all of the energy generated at the heat source is used to melt the weld metal. There are two heat transfer mechanisms at work, both of which reduce the amount of generated heat that is used by the welding process. The situation is depicted in **Figure 8**. The first mechanism involves the transfer of heat between the heat source and the surface of the work. This process has a certain heat transfer factor f_1 , defined as the ratio of the actual heat received by the workpiece divided by the total heat generated at the source. The second mechanism involves the conduction of heat away from the weld area to be dissipated throughout the work metal, so that only a portion of the heat transferred to the surface is available for melting. This melting factor f_2 is the proportion of heat received at the work surface that can be used for melting. The combined effect of these two factors is to reduce the heat energy available for welding as follows:

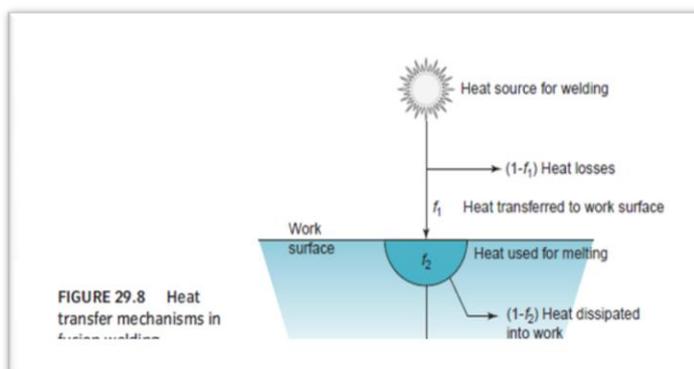
$$H_w = f_1 f_2 H \dots\dots\dots (3)$$

where

H_w = net heat available for welding, J (Btu), f_1 = heat transfer factor, f_2 = the melting factor, and H = the total heat generated by the welding process, J (Btu). The factors f_1 and f_2 range in value between zero and one. It is appropriate to separate f_1 and f_2 in concept, even though they act in concert during the welding process.

The heat transfer factor f_1 is determined largely by the welding process and the capacity to convert the power source (e.g., electrical energy) into usable heat at the work surface. Arc-welding processes are relatively efficient in this regard, while oxyfuel gas-welding processes are relatively inefficient.

The melting factor f_2 depends on the welding process, but it is also influenced by the thermal properties of the metal, joint configuration, and work thickness. Metals with high thermal conductivity, such as aluminum and copper, present a problem in welding because of the rapid dissipation of heat away from the heat contact area. The problem is exacerbated by welding heat sources with low energy densities (e.g., oxyfuel welding) because the heat input is spread over a larger area, thus facilitating conduction into the work. In general, a high power density combined with a low conductivity work material results in a high melting factor .



We can now write a balance equation between the energy input and the energy needed for welding:

$$H_w = U_m V \dots\dots\dots(4)$$

where

H_w = net heat energy used by the welding operation, J (Btu); U_m = unit energy required to melt the metal, J/mm³ (Btu/in³); and V = the volume of metal melted, mm³ (in³).

Most welding operations are rate processes; that is, the net heat energy H_w is delivered at a given rate, and the weld bead is made at a certain travel velocity. This is characteristic for example of most arc-welding, many oxyfuel gas-welding operations, and even some resistance welding operations. It is therefore appropriate to express Eq. (30) as a rate balance equation:

$$RH_w = U_m RWV \dots\dots\dots(5)$$

Where

RH_w = rate of heat energy delivered to the operation for welding, J/s = W (Btu/min); and

RWV = volume rate of metal welded, mm³/s (in³/min). In the welding of a continuous bead, the volume rate of metal welded is the product of weld area A_w and travel velocity v . Substituting these terms into the above equation, the rate balance equation can now be expressed as

$$RH_w = f_1 f_2 RH = U_m A_w v \dots\dots\dots(6)$$

Where

f_1 and f_2 are the heat transfer and melting factors; RH = rate of input energy generated by the welding power source, W (Btu/min); A_w = weld cross-sectional area, mm² (in²); and v = the travel velocity of the welding operation, mm/s (in/min).

8- Features of A Fusion - Welded Joints

Most weld joints are fusion welded. As illustrated in the cross-sectional view of **Figure 9** (a), a typical fusion-weld joint in which filler metal has been added consists of several zones: **(1) fusion zone, (2) weld interface, (3) heat-affected zone, and (4) unaffected base metal zone.**

The fusion zone consists of a mixture of filler metal and base metal that have completely melted. This zone is characterized by a high degree of homogeneity among the component metals that have been melted during welding. The mixing of these components is motivated largely by convection in the molten weld pool. Solidification in the fusion zone has similarities to a casting process. In 8significant difference between solidification in casting and in welding is that epitaxial grain growth occurs in welding. The reader may recall that in casting, the metallic grains are formed from the melt by nucleation of solid particles at the mold wall, followed by grain growth. In welding, by contrast, the nucleation stage of solidification is avoided by the mechanism of epitaxial grain growth, in which atoms from the molten pool solidify on preexisting lattice sites of the adjacent solid base metal.

Consequently, the grain structure in the fusion zone near the heat-affected zone tends to mimic the crystallographic orientation of the surrounding heat-affected zone. Further into the fusion zone, a preferred orientation develops in which the grains are roughly perpendicular to the boundaries of the weld interface. The resulting structure in the solidified fusion zone tends to feature coarse columnar grains, as depicted in **Figure 9(b)**. The grain structure depends on various factors,

including welding process, metals being welded (e.g., identical metals vs. dissimilar metals welded), whether a filler metal is used, and the feed rate at which welding is accomplished.

The second zone in the weld joint is **the weld interface**, a narrow boundary that separates the fusion zone from the heat-affected zone. The interface consists of a thin band of base metal that was melted or partially melted (localized melting within the grains) during the welding process but then immediately solidified before any mixing with the metal in the fusion zone. Its chemical composition is therefore identical to that of the base metal.

The third zone in the typical fusion weld is **the heat-affected zone (HAZ)**. The metal in this zone has experienced temperatures that are below its melting point, yet high enough to cause microstructural changes in the solid metal. The chemical composition in the heat-affected zone is the same as the base metal, but this region has been heat treated due to the welding temperatures so that its properties and structure have been altered.

The amount of metallurgical damage in the HAZ depends on factors such as the amount of heat input and peak temperatures reached, distance from the fusion zone, length of time the metal has been subjected to the high temperatures, cooling rate, and the metal's thermal properties. The effect on mechanical properties in the heat-affected zone is usually negative, and it is in this region of the weld joint that welding failures often occur.

As the distance from the fusion zone increases, the **unaffected base metal zone** is finally reached, in which no metallurgical change has occurred. Nevertheless, the base metal surrounding the HAZ is likely to be in a state of high residual stress, the result of shrinkage in the fusion zone.

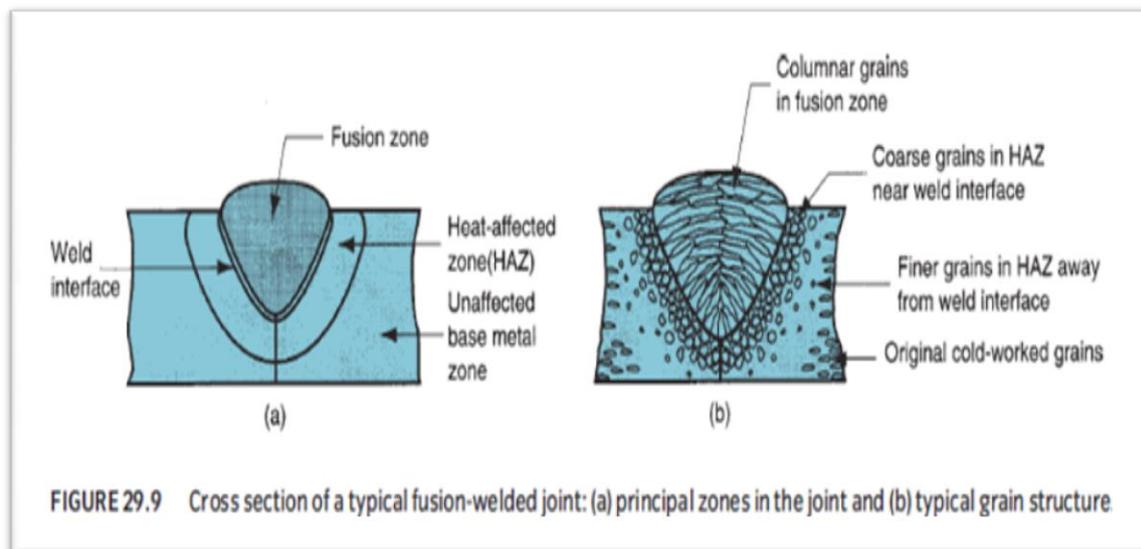


FIGURE 29.9 Cross section of a typical fusion-welded joint: (a) principal zones in the joint and (b) typical grain structure

Reference

Mikell P. Groover , " Fundamentals of Modern Manufacturing ,Materials ,Processes ,and Systems" ,4th edition, JOHN WILEY & SONS, INC.,2010

4 Shielded Metal Arc Welding*

* Abbreviated MMA (Manual metal arc welding). American designation: shielded metal arc welding (SMAW).

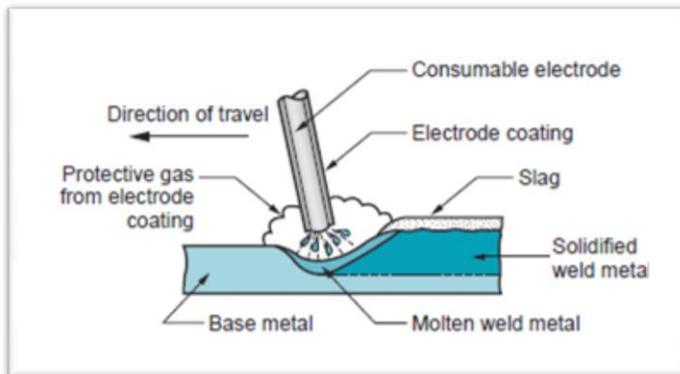
Shielded metal arc welding (SMAW) is an AW process that uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding. The process is illustrated in **Figure 4.1**. The welding stick (SMAW is sometimes called **stick welding**) is typically 225 to 450mm (9–18 in) long and 2.5 to 9.5mm (3/32–3/8 in) in diameter. The filler metal used in the rod must be compatible with the metal to be welded, the composition usually being very close to that of the base metal. The coating consists of powdered cellulose (i.e., cotton and wood powders) mixed with oxides, carbonates, and other ingredients, held together by a silicate binder. Metal powders are also sometimes included in the coating to increase the amount of filler metal and to add alloying elements. The heat of the welding process melts the coating to provide a protective atmosphere and slag for the welding operation. It also helps to stabilize the arc and regulate the rate at which the electrode melts.

During operation the bare metal end of the welding stick (opposite the welding tip) is clamped in an electrode holder that is connected to the power source. The holder has an insulated handle so that it can be held and manipulated by a human welder. Currents typically used in SMAW range between 30 and 300 A at voltages from 15 to 45 V. Selection of the proper power parameters depends on the metals being welded, electrode type and length, and depth of weld penetration required. Power supply, connecting cables, and electrode holder can be bought for a few thousand dollars.

Shielded metal arc welding is usually performed manually. Common applications include construction, pipelines, machinery structures, shipbuilding, job shop fabrication, and repair work. It is preferred over oxyfuel welding for thicker sections—above 5 mm (3/16 in) because of its higher power density. The equipment is portable and low cost, making SMAW highly versatile and probably the most widely used of the AW processes. Base metals include steels, stainless steels, cast irons, and certain nonferrous alloys. It is not used or seldom used for aluminum and its alloys, copper alloys, and titanium.

A disadvantage of shielded metal arc welding as a production operation is the use of the consumable electrode stick. As the sticks are used up, they must periodically be changed. This reduces the arc time with this welding process. Another limitation is the current level that can be used. Because the electrode length varies during the operation and this length affects the resistance heating of the electrode, current levels must be maintained within a safe range or the coating will overheat and melt prematurely when starting a new welding stick. Some of the other AW processes overcome the limitations of welding stick length in SMAW by using a continuously fed wire electrode

Figure 4.1 Shielded metal arc welding (SMAW)



Arc Energy

The arc is generated by electrons (small negatively charged particles) flowing from the - ve to the + ve pole and the electrical energy is changed in the arc into heat and light. Approximately two-thirds of the heat is developed near the -ve pole, which burns into the form of a crater, the temperature near the crater being about 6000-7000°C, while the remaining third is developed near to the + ve pole. As a result an electrode connected to the + pole will burn away 50% faster than if connected to the - ve pole. For this reason it is usual to connect medium-coated electrodes and bare rods to the - ve pole, so that they will not burn away too quickly. Heavily coated rods are connected to the +ve pole because, due to the extra heat required to melt the heavy coating, they burn more slowly than the other types of rods when carrying the same current. The thicker the electrode used, the more heat is required to melt it, and thus the more current is required. The welding current may vary from 20 to 600 A in manual metal arc welding.

When alternating current is used, heat is developed equally at plate and rod, since the electrode and plate are changing polarity at the frequency of the supply. If a bare wire is used as the electrode it is found that the arc is difficult to control, the arc stream wandering hither and thither over the molten pool. The globules are being exposed to the atmosphere in their travel from the rod to the pool and absorption of oxygen and nitrogen takes place even when a short arc is held. The result is that the weld tends to be porous and brittle.

The greater the volts drop across the arc the greater the energy liberated in heat for a given current.

Arc energy is usually expressed in kilojoules per millimetre length of the weld (kJ/mm):-

$$\text{Arc energy (kJ/mm)} = \frac{\text{arc voltage} \times \text{welding current}}{\text{welding speed (mm/s)} \times 1000} \dots\dots\dots(4.1)$$

The volts drop can be varied by altering the type of gas shield liberated by the electrode covering, hydrogen giving a higher volts drop than carbon dioxide for example. As the length of the arc increases so does the voltage drop, but since there is an increased resistance in this long arc the current is decreased. Long arcs are difficult to control and maintain and they lower the efficiency of the gas shield because of the greater length. As a result, absorption of oxygen and nitrogen from the atmosphere can take place, resulting in poor mechanical properties of the weld. It is essential that the welder should keep as short an arc as possible to ensure sound welds.

Electrode efficiency.

The efficiency of an electrode is the mass of metal actually deposited compared with the mass of that portion of the electrode consumed. It can be expressed as a percentage thus:

$$\text{efficiency \%} = \frac{\text{mass of metal deposited}}{\text{mass of metal of the electrode consumed}} \times 100 \dots\dots\dots(4.2)$$

With ordinary electrodes the efficiency varies from 75 % to 95 % but with electrodes containing metallic components in the covering the efficiency can approach 200 % (e.g. electrodes containing iron powder). In the electrode classification (British), efficiencies of 110% and above are indicated by a three-digit figure in the additional section of the electrode coding, giving the efficiency rounded to the nearest 10, with values ending in 5 being rounded up (BS 639 (1986)).

Electrode classification (British)

Abridged classification for covered carbon and carbon-manganese steel electrodes for manual metal arc welding. BS 639 (1986)

Note: This classification is for deposited weld metal having a tensile strength not greater than 650 N/mm². Students should study the whole text of BS 639 (1986), which gives full details of the classification together with the tests involved. Weld metals with tensile strength greater than 650 N/mm² are dealt with in BS 2493 and BS 2926.

The classification is denoted by a code consisting of two parts: (a) a general code, followed by (b) an additional code in parentheses, for

example E 43 2 2 RR (2 1)

(a) **General code** (strength, toughness and covering (STC) code). There are five elements in the general code (in the order given)

- (1) the letter E indicating a covered electrode for manual metal arc welding
- (2) two digits indicating the strength (tensile, yield and elongation properties of the weld metal)
- (3) one digit indicating the temperature for a minimum average impact value of 28 J
- (4) one digit indicating the temperature for a minimum average impact value of 47 J
- (5) either one or two letters indicating the type of covering, namely:
B - basic; BB - basic, high efficiency; C - cellulosic; R - rutile;
RR - rutile heavy coated; S - other types

Table 4.1 indicates the types of electrode flux coatings

(b) **Additional code:** This has four elements, of which (1) and (4) are included only if appropriate.

(1) where appropriate, three digits indicating the nominal electrode efficiency included only if this is equal to, or greater than 110, the figures being rounded off to the nearest multiple of 10, those of 5 and upwards being rounded up.

(2) a digit indicating the recommended welding positions for the electrode:

- 1 - all positions,
- 2 - all positions except vertical/down,
- 3 - flat and for fillet welds, horizontal/vertical,
- 4 - flat,
- 5 - flat, vertical/down and, for fillet welds, horizontal/vertical,
- 9 - any other position or combination of positions not classified above.

(3) a digit indicating the power requirements

(4) a letter H, where appropriate, indicating a hydrogen controlled electrode.

Table 5. *Types of electrode flux coverings*

Class	Composition of covering	Characteristics
C cellulosic	Organic materials containing cellulose (C ₄ H ₁₀ O ₃) _x	Voluminous gas shield; good penetration; fast welding speeds; easily removable slag. Suitable for steel welding a.c. or d.c. electrode +ve. Used for first (stringer) run in downhill pipe-line welding. High level of hydrogen.
B basic	Calcium carbonate (CaCO ₃), calcium fluoride (CaF ₂) and other basic carbonates	The calcium carbonate decomposes in the arc heat to release carbon dioxide which gives the gas shield. The calcium oxide (CaO) combines with the calcium fluoride to form a basic slag having a low melting point. The low hydrogen content of the weld metal results in a weld that is resistant to solidification cracking and to a high sulphur content in the steel. Because there are no organic or hydrated materials in the covering the electrodes can be baked at high temperature giving a low level of hydrogen in the weld metal and reducing the danger of cold cracking, particularly in highly restrained joints and thick sections. Because of the relatively small gas shield, a short arc should be used and the electrodes are suitable for a.c. or d.c. electrode +ve. They should be stored under warm dry conditions and preferably baked before use.
BB basic high efficiency	Similar to basic electrode covering but have additional metallic materials (e.g. iron powder) in the covering which raise the efficiency to 130% and more	These electrodes are suitable for welding in the flat and horizontal/vertical position with a greatly increased rate of metal deposition. Their high efficiency covering makes them unsuitable for welding in the vertical and overhead positions. They can be used either a.c. or d.c., generally with electrode +ve. Efficiency is indicated by a three-figure digit beginning the additional coding.

Class	Composition of covering	Characteristics
R rutile	Titanium dioxide (rutile) and other hydrated minerals and/or organic cellulose materials	Easy to use, with a smooth weld finish and medium penetration. High level of hydrogen in the weld metal limits their use in thick sections or restrained joints. Suitable for a.c. or d.c.; the fast freezing of weld metal and fluid slag makes them suitable for vertical and overhead welding.
RR rutile heavy coating	Similar covering to the previous rutile electrode but containing, in addition, metallic substances (e.g. iron powder), which raise the efficiency to 130% or more.	Similar characteristics to rutile electrodes but generally unsuitable for vertical and overhead welding because of increased slag. Increased rate of metal deposition. Efficiency is indicated by a three-figure digit beginning the additional coding.
S other types		This class includes electrodes that do not fall into any of the previous classes. They range from little used types, such as those with acid covering (containing oxides and carbonates of lime and manganese with deoxidizers such as ferromanganese), to the oxide types (containing iron oxide with or without manganese oxide and silicates). This class also includes any newly developed flux systems. Manufacturer's advice should be followed when using them.

Electrode classification (American)

American Welding Society (AWS) electrode classification: abridged specification for covered carbon steel arc welding electrodes ANSF/AWS A5 1 81 (Reprint 1984)

In the AWS classification a four-digit number is used, preceded by the letter E (indicating a covered arc welding electrode).

The first two digits indicate the minimum tensile strength of the weld metal deposited in thousands of pounds force per square inch (1000 psi) as shown in **Table 4.2**.

For example, **E70XX** could represent an electrode giving weld metal having a minimum tensile strength of 72000 psi or 72 ksi (500 MPa or 500 N/mm²). Details of chemical composition, mechanical usability and soundness (radiographic) test, all-weld-metal tension test and impact (Charpy) test are given in the specification.

The last two digits indicate the characteristics of the covering (see **Table 4.3**).

Table 6. AWS electrode classification

AWS classification	Type of covering	Capable of producing satisfactory welds in position shown ^a	Type of current ^b
E60 series electrodes			
E6010	High cellulose sodium	F, V, OH, H	DCEP
E6011	High cellulose potassium	F, V, OH, H	AC or DCEP
E6012	High titania sodium	F, V, OH, H	AC or DCEN
E6013	High titania potassium	F, V, OH, H	AC or DC, either polarity
E6020	High iron oxide	H-fillets	AC or DCEN
E6022 ^c	High iron oxide	F	AC or DC, either polarity
E6027	High iron oxide, iron powder	H-fillets, F	AC or DCEN
E70 series electrodes			
E7014	Iron powder, titania	F, V, OH, H	AC or DC, either polarity
E7015	Low hydrogen sodium	F, V, OH, H	DCEP
E7016	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E7018	Low hydrogen potassium, iron powder	F, V, OH, H	AC or DCEP
E7024	Iron powder, titania	H-fillets, F	AC or DC, either polarity
E7027	High iron oxide, iron powder	H-fillets, F	AC or DCEN
E7028	Low hydrogen potassium, iron powder	H-fillets, F	AC or DCEP
E7048	Low hydrogen potassium, iron powder	F, OH, H, V-down	AC or DCEP

Note the American use of AC and DC for alternating current and direct current.

^a F = flat, H = horizontal, H-fillets = horizontal fillets, V-down = vertical down.

V = vertical } for electrodes 3/16 in and under, except 5/32 in and under for classifications E7014, E7015, E7016, E7018.
OH = overhead }

^b DCEP direct current electrode positive (DC reverse polarity). DCEN direct current electrode negative (DC straight polarity)

^c E6022 classification electrodes are for single-pass welds.

Examples of A WS classification

Example 1

E6013: Electrode with weld metal tensile strength 60 ksi or 412 N/mm² high rutile covering bonded with potassium silicate AC or DC either polarity.

Table 4.3. Characteristics of coverings

Exx10	High cellulose, bonded with sodium silicate. Deeply penetrating, forceful spray-type arc. Thin friable slag.
Exx11	Similar to Exx10 but bonded with potassium silicate to allow use on AC or DC; covering bonded with sodium silicate.
Exx12	High rutile. Quiet arc, medium penetration.
Exx13	Similar to Exx12 but bonded with potassium silicate and other easily ionized materials. Fluid slag, easily removed.
Exx14	Similar to Exx12 and Exx13 types with the addition of iron powder.
Exx15	Basic low hydrogen type bonded with sodium silicate. For high tensile steels.
Exx16	Similar to Exx15 but bonded with potassium silicate.
Exx18	Covering similar to Exx15 and Exx16 but with addition of iron powder.
Exx20	High iron oxide coating bonded with sodium silicate.
Exx24	Similar to Exx12 and Exx13. Heavily coated plus iron powder.
Exx27	Flux ingredients similar to Exx20 with the addition of iron powder.
Exx28	Similar to Exx18 but with heavier covering. Low hydrogen, potassium silicate as binder. Flat and horizontal fillets.
Exx48	Similar to Exx28, low hydrogen but suitable for most positions.

* American National Standards Institute

Example 2

E7018: Electrode with weld metal of tensile strength 70 ksi, with basic covering, iron powder, low hydrogen. Bonded with potassium silicate F, V, OH, H, AC or DCEP. Core wire for all electrodes in this specification is usually of composition 0.10% carbon, 0.45% manganese, 0.03% sulphur, 0.02% phosphorus and 0.01 % silicon.

Table 9. American Welding Society (AWS) abridged classification for low-alloy steel covered arc welding electrodes. A5.5-81 (reprinted 1985)

The higher tensile strength electrodes, such as E8010, which do not have low hydrogen coverings are used for pipe welding and are usually matched to the pipe.

AWS classification	Type of covering	Capable of producing satisfactory welds in position shown	Type of current
<i>E70 series: minimum tensile strength of deposited metal 70000 psi (480 MPa)</i>			
E7010-X*	High cellulose sodium	F, V, OH, H	DCEP
E7011-X	High cellulose potassium	F, V, OH, H	AC or DCEP
E7015-X	Low hydrogen sodium	F, V, OH, H	DCEP
E7016-X	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E7018-X	Iron powder low hydrogen	F, V, OH, H	AC or DCEP
E7020-X	High iron oxide	H-fillets F	AC or DCEN AC or DC, either polarity
E7027-X	Iron powder iron oxide	H-fillets F	AC or DCEN AC or DC, either polarity
<i>E80 series: minimum tensile strength of deposited metal 80000 psi (550 MPa)</i>			
E8010-X	High cellulose sodium	F, V, OH, H	DCEP
E8011-X	High cellulose potassium	F, V, OH, H	AC or DCEP
E8013-X	High titania potassium	F, V, OH, H	AC or DC, either polarity
E8015-X	Low hydrogen sodium	F, V, OH, H	DCEP
E8016-X	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E8018-X	Iron powder low hydrogen	F, V, OH, H	AC or DCEP
<i>E90 series: minimum tensile strength of deposited weld metal 90000 psi (620 MPa)</i>			
E9010-X	High cellulose sodium	F, V, OH, H	DCEP
E9011-X	High cellulose potassium	F, V, OH, H	AC or DCEP
E9013-X	High titania potassium	F, V, OH, H	AC or DC, either polarity
E9015-X	Low hydrogen sodium	F, V, OH, H	DCEP
E9016-X	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E9018-X	Iron powder low hydrogen	F, V, OH, H	AC or DCEP
<i>E100 series: minimum tensile strength of deposited metal 100000 psi (690 MPa)</i>			
E10010-X	High cellulose sodium	F, V, OH, H	DCEP
E10011-X	High cellulose potassium	F, V, OH, H	AC or DCEP
E10013-X	High titania potassium	F, V, OH, H	AC or DC, either polarity
E10015-X	Low hydrogen sodium	F, V, OH, H	DCEP
E10016-X	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E10018-X	Iron powder, low hydrogen	F, V, OH, H	AC or DCEP
<i>E110 series: minimum tensile strength of deposited weld metal 110000 psi (760 MPa)</i>			
E11015-X	Low hydrogen sodium	F, V, OH, H	DCEP
E11016-X	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E11018-X	Iron powder, low hydrogen	F, V, OH, H	AC or DCEP
<i>E120 series: minimum tensile strength of deposited weld metal 120000 psi (830 MPa)</i>			
E12015-X	Low hydrogen sodium	F, V, OH, H	DCEP
E12016-X	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E12018-X	Iron powder, low hydrogen	F, V, OH, H	AC or DCEP

* X stands for the various suffixes A1, B1, C1, etc., which denote the types of chemical composition of the electrodes (see Table 10).

Table 10. *Chemical composition of electrodes*

Suffix	Type of steel	Example	Suffix	Type of steel	Example
A1	Carbon-molybdenum	E7011-A1	C2L	Nickel steel	E7016-C2L
B1	Chromium-molybdenum	E8016-B1	C3 ^c	Nickel steel	E8018-C3'
B2	Chromium-molybdenum	E8018-B2	NM ^d	Nickel-molybdenum	E8018-NM'
B2L	Chromium-molybdenum	E8015-B2L	D1	Manganese-molybdenum	E9018-D1
B3	Chromium-molybdenum	E9016-B3	D3	Manganese-molybdenum	E8016-D3
B3L	Chromium-molybdenum	E9018-B3L	D2	Manganese-molybdenum	E10015-D2
B4L	Chromium-molybdenum	E8015-B4L	G	All other low alloy steel electrodes	E7020-G
B5	Chromium-molybdenum	E8016-B5	M	Military specification	E11018-M
C1	Nickel steel	E8016-C1	W	Containing small % copper	E7018-W
C1L	Nickel steel	E7018-C1L			
C2	Nickel steel	E8018-C2			

L indicates a low carbon steel, generally less than 0.15%.

^c These classifications conform to those covered by military specifications for similar compositions.

^d Copper shall be 0.10% max and aluminium 0.05% max for E8018-NM electrodes.

Example

2NiB. *A 2% nickel steel electrode (Ni 2.0-2.75%) with basic covering (AWS E80XX-C1)*

Most low-alloy steel electrodes have a core wire of rimming steel (steel that has not been fully deoxidized before casting) with the alloying elements added to the covering. Under certain conditions, such as in pipe welding, the thickness of the covering makes positional welding difficult so the cellulosic covered electrodes have a core wire of the correct alloy steel e.g. chromium-molybdenum type (1CrMo, 2CrMo and 5CrMo).