

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.

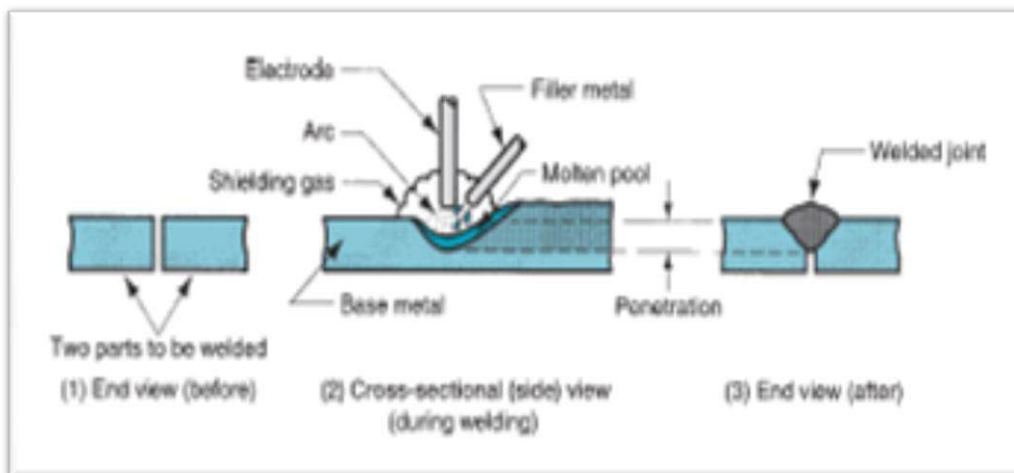


Figure 1 Basics of arc welding: (1) before the weld; (2) during the weld (the base metal is melted and filler metal is added to the molten pool); and (3) the completed weldment.

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.

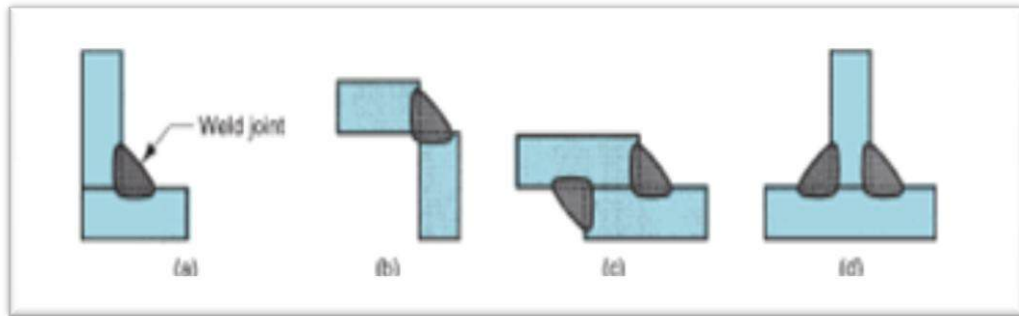
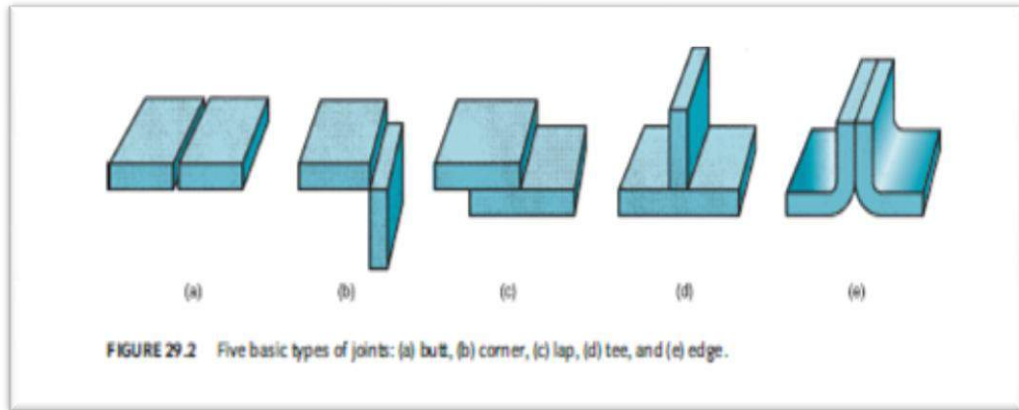


Figure 3 Various forms of fillet welds: (a) inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; and (d) double fillet tee joint. Dashed lines show the original part edges.

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.

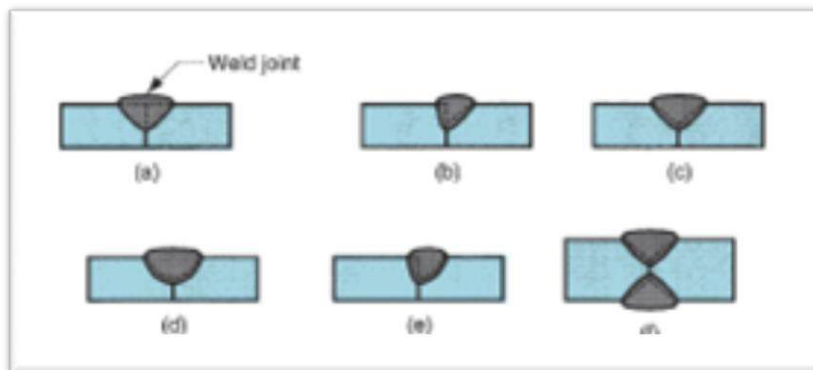


Figure 4 Some typical groove welds (a) square groove weld, one side; (b) single bevel groove weld; (c) single V-groove weld; (d) single U-groove weld; (e) single J-groove weld; (f) double V-groove weld for thicker sections. Dashed lines show the original part edges.

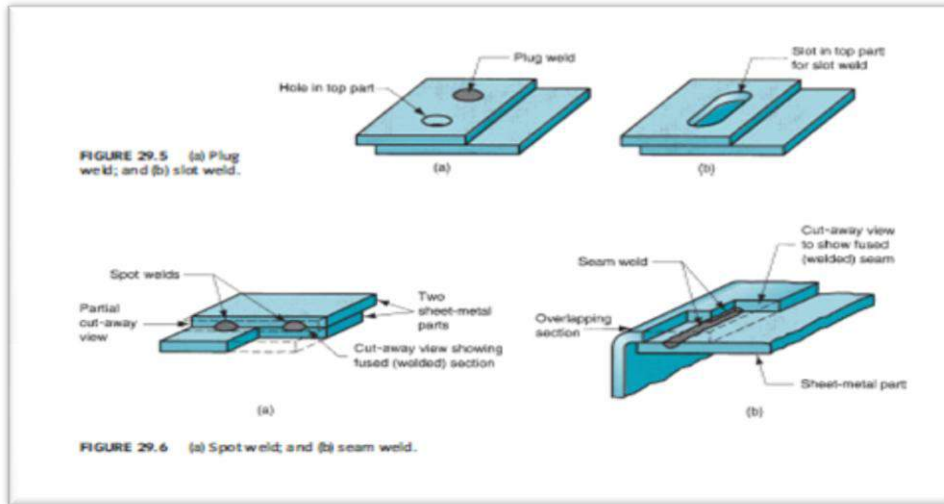


Figure 5 (a) Plug weld; and (b) slot weld. **Figure 6** a) Spot weld; and (b) seam weld.

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.

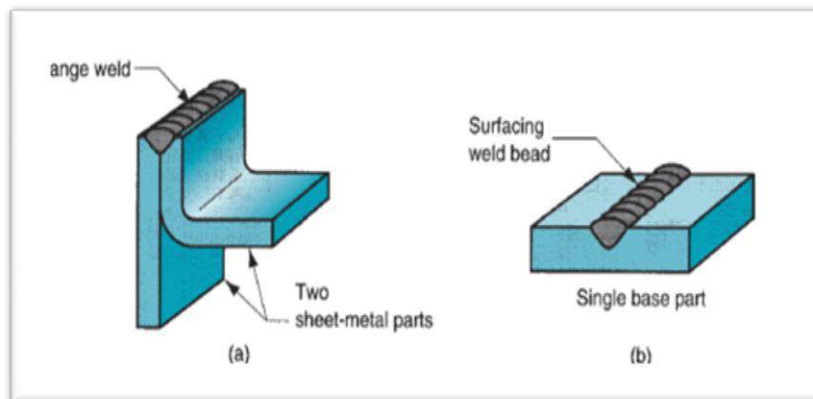


Figure 7 (a) Flange welds and (b) surfacing welds

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	
	$^{\circ}\text{K}^a$	$^{\circ}\text{R}^b$		$^{\circ}\text{K}^a$	$^{\circ}\text{R}^b$
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 .

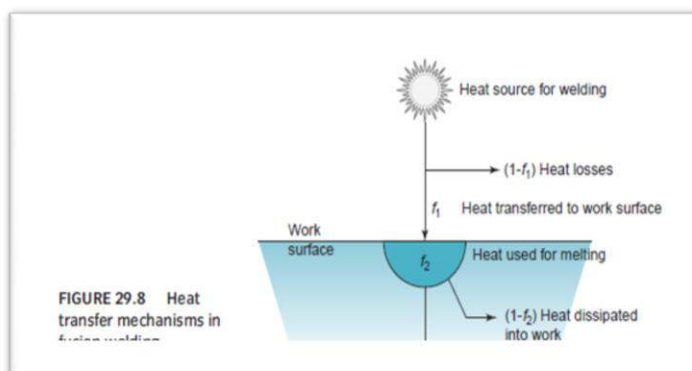


FIGURE 29.8 Heat transfer mechanisms in fusion welding.

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.

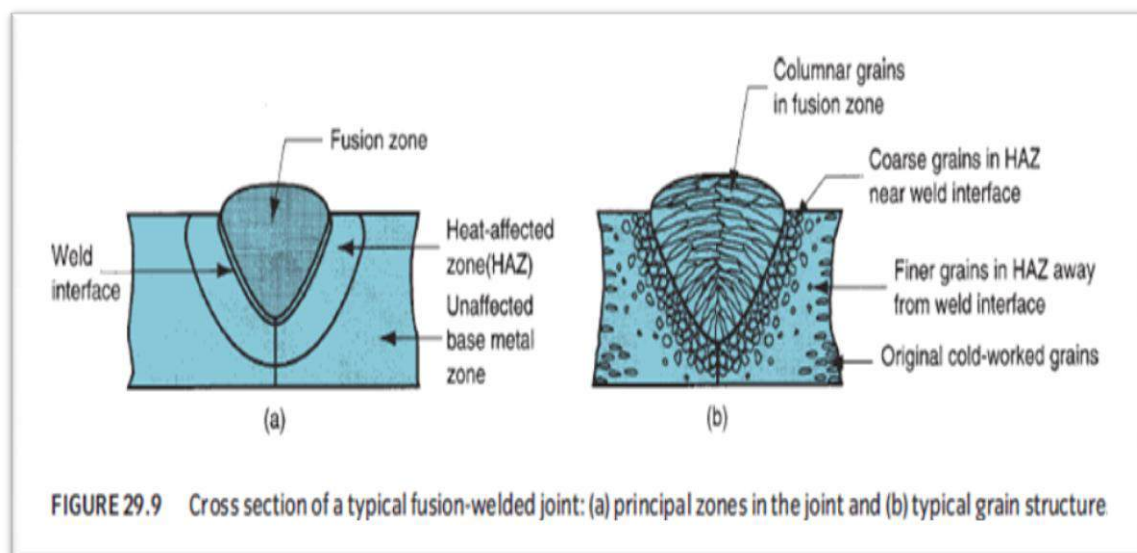


FIGURE 29.9 Cross section of a typical fusion-welded joint: (a) principal zones in the joint and (b) typical grain structure

Reference

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