Part VIII Joining and Assembly Processes

28 Fundamentals of Welding

This part of the book considers processes used to join two or more parts into an assembled entity. These processes are labeled in the lower stem of Figure 1.5. 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. Mechanical assembly is covered in Chapter 31. Some of these methods allow for easy disassembly, while others do not. Brazing, soldering, and adhesive bonding are discussed in Chapter 30. Coverage of the joining and assembly processes begins with welding, addressed in this chapter and the following.

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. Here, the discussion will focus on metals.

Welding is a relatively new process (Historical Note 28.1). Its commercial and technological importance derives from the following:

➢ Welding provides a permanent joint. The welded parts become a single entity.

➢ 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.

➢ 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.

➢ 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):

➢ 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.

➢ Most welding processes are inherently dangerous because they involve the use of high energy.

➢ Because 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.

➢ The welded joint can suffer from certain quality defects that are difficult to detect. The defects can reduce the strength of the joint.

Historical Note 28.1   *Origins of welding*

Although welding is considered a relatively new process as practiced today, its origins can be traced to ancient times. Around 1000 BCE, the Egyptians and others in the eastern Mediterranean area learned to accomplish forge welding (Section 29.5.2). It was a natural extension of hot forging, which they used to make weapons, tools, and other implements. Forge-welded articles of bronze have been recovered by archeologists from the pyramids of Egypt. From these early beginnings through the Middle Ages, the blacksmith trade developed the art of welding by hammering to a high level of maturity. Welded objects of iron and other metals dating from these times have been found in India and Europe.

It was not until the 1800s that the technological foundations of modern welding were established. Two important discoveries were made, both attributed to English scientist Sir Humphrey Davy: (1) the electric arc, and (2) acetylene gas.

Around 1801, Davy observed that an electric arc could be struck between two carbon electrodes. However, not until the mid-1800s, when the electric generator was invented, did electrical power become available in amounts sufficient to sustain **arc welding**. It was a Russian, Nikolai Benardos, working out of a laboratory in France, who was granted a series of patents for the carbon arc–welding process (one in England in 1885, and another in the United States in 1887). By the turn of the century, carbon arc welding had become a popular commercial process for joining metals.

Benardos' inventions seem to have been limited to carbon arc welding. In 1892, an American named Charles Coffin was awarded a U.S. patent for developing an arc–welding process utilizing a metal electrode. The unique feature was that the electrode added filler metal to the weld joint (the carbon arc process does not deposit filler). The idea of coating the metal electrode (to shield the welding process from the atmosphere)

was developed later, with enhancements to the metal arc–welding process being made in England and Sweden starting around 1900.

Between 1885 and 1900, several forms of **resistance welding** were developed by Elihu Thompson. These included spot welding and seam welding, two joining methods widely used today in sheet metalworking.

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.

28.1 Overview of Welding Technology

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.

28.1.1 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. The welding processes can be divided into two major groups: (1) fusion welding and (2) solid-state welding.

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 28.1. Some arc-welding operations also apply pressure during the process and most utilize a filler metal.

FIGURE 28.1   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.

(1) End view (before)

(2) Cross-sectional (side) view (during welding)

(3) End view (after)
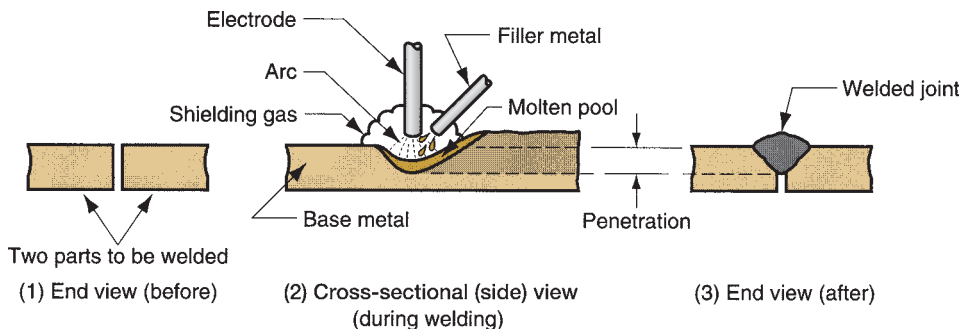
➢ *Resistance welding* (RW). Resistance welding achieves coalescence using heat from electrical resistance to the flow of a current passing between the faying surfaces of two parts held together under pressure.

➢ *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.

➢ 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 (Sections 25.3.4 and 25.3.5).

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.

The various welding processes are described in greater detail in Chapter 29. The preceding survey should provide a sufficient framework for the discussion of welding terminology and principles in the present chapter.

28.1.2   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 [1]. 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 position-ers are used for this purpose. A *welding fixture* is a device for clamping and hold-ing 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 posi-tion 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 tem-peratures 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 weld-ing, 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 fa-cilities 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 mechaniza-tion 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 per-forms 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, auto-matic 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 (Sec-tion 37.4). 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 al-lows 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 spot welding on car bodies (Figure 37.16).

28.2 The Weld Joint

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.

28.2.1 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 28.2, 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).

28.2.2 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.
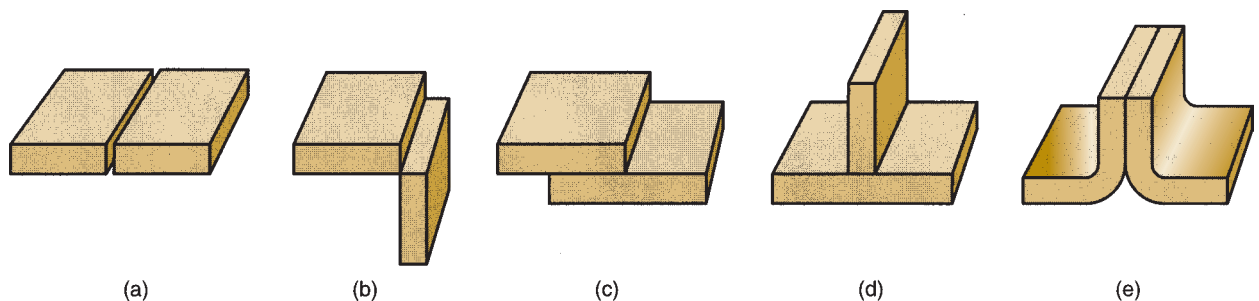

(a)   (b)   (c)   (d)   (e)

FIGURE 28.2   Five basic types of joints: (a) butt, (b) corner, (c) lap, (d) tee, and (e) edge.
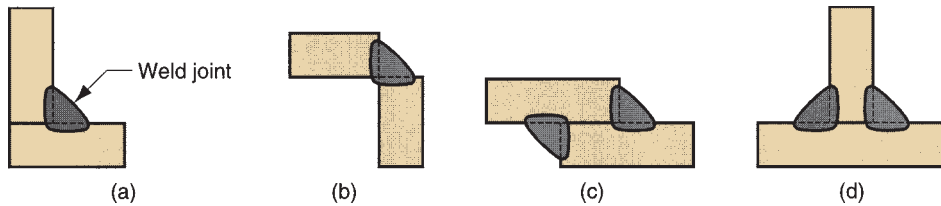
FIGURE 28.3   Various forms of fillet welds: (a) inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; and (d) double fillet tee joint. Dashed lines show the original part edges.

A *fillet weld* is used to fill in the edges of plates created by corner, lap, and tee joints, as in Figure 28.3. 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 single or double sides, as shown in Figure 28.4. 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 28.5, using one or more holes or slots in the top part and then filling with filler metal to fuse the two parts together.

FIGURE 28.4   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.
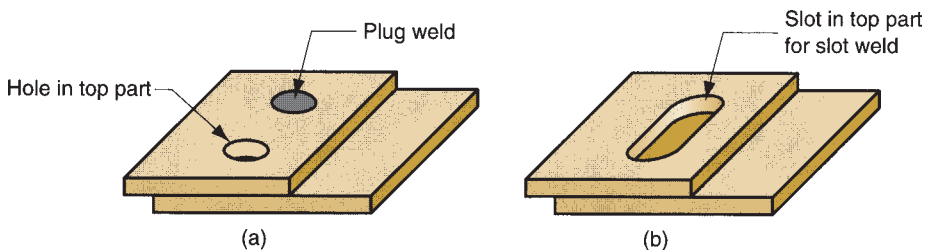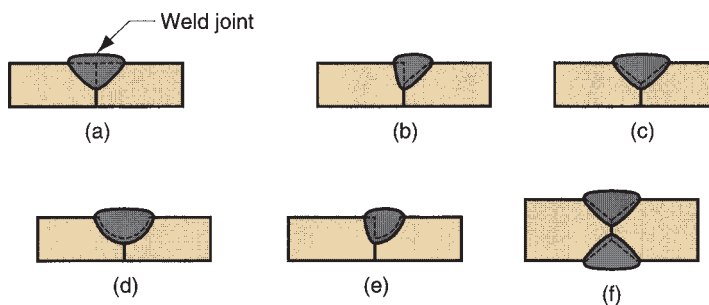

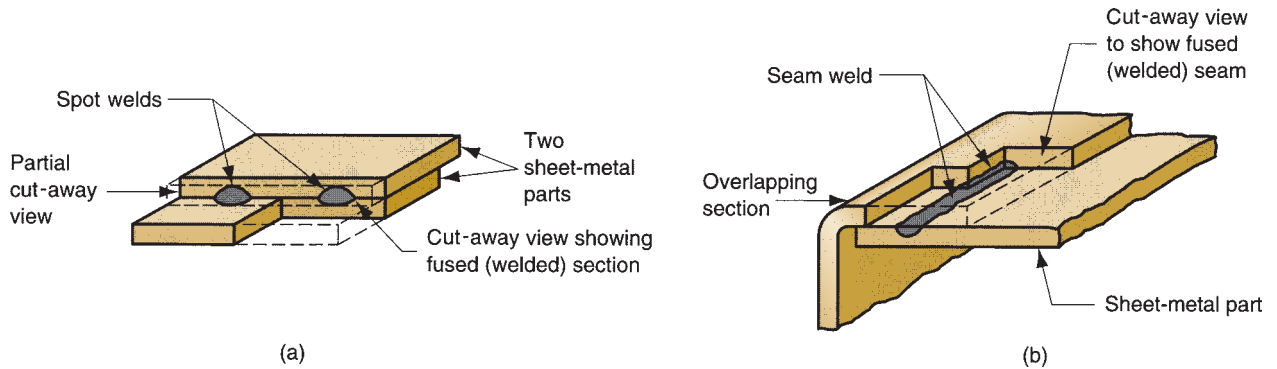**FIGURE 28.5**   (a) Plug weld and (b) slot weld.

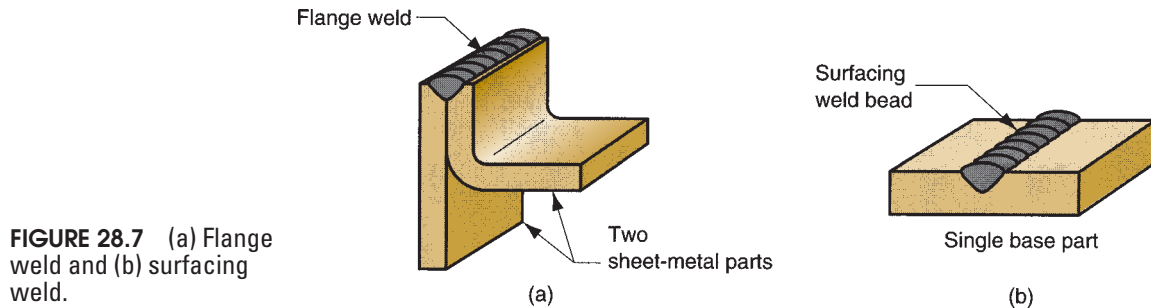**FIGURE 28.6**   (a) Spot weld and (b) seam weld.

FIGURE 28.7   (a) Flange weld and (b) surfacing weld.

Spot welds and seam welds, used for lap joints, are diagrammed in Figure 28.6. 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.

Flange welds and surfacing welds are shown in Figure 28.7. 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 28.7(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.

28.3 Physics of Welding

Although several coalescing mechanisms are available for welding, fusion is by far the most common means. This section considers the physical relationships that allow fusion welding to be performed. Power density and its importance are first examined, and then the heat and power equations that describe a welding process are defined.

28.3.1 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 10^5 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 28.1 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 600°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.

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

$$PD = \frac{P}{A} \tag{28.1}$$

where PD = power density, W/mm^2 ($Btu/sec-in^2$); P = power entering the surface, W (Btu/sec); and A = surface area over which the energy is entering, mm^2 (in^2). The issue is more complicated than indicated by Equation (28.1). 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 postheating behind it. Another complication is that power density is not uniform throughout the affected surface; it is distributed as a function of area, as demonstrated by the following example.

TABLE • 28.1 Comparison of several fusion welding processes on the basis of their power densities.

Welding Process	Approximate Power Density	
	W/mm²	Btu/sec-in²
Oxyfuel welding	10	6
Arc welding	50	30
Resistance welding	1000	600
Laser beam welding	9000	5000
Electron beam welding	10,000	6000

Example 28.1 Power density in welding	A heat source transfers 3000 W to the surface of a metal part. The heat impinges the surface in a circular area, with intensities varying inside the circle. The distribution is as follows: 70% of the power is transferred within a circle of diameter = 5 mm, and 90% is transferred within a concentric circle of diameter = 12 mm. What are the power densities in (a) the 5-mm-diameter inner circle and (b) the 12-mm-diameter ring that lies around the inner circle?

Solution: (a) The inner circle has an area $A = \dfrac{\pi(5)^2}{4} = 19.63$ mm^2

The power inside this area $P = 0.70 \times 3000 = 2100$ W

Thus the power density $PD = \dfrac{2100}{19.63} = $ **107 W/mm²**

(b) The area of the ring outside the inner circle is $A = \dfrac{\pi(12^2 - 5^2)}{4} = 93.4$ mm^2

The power in this region $P = 0.9\,(3000) - 2100 = 600$ W.

The power density is therefore PD$\dfrac{600}{93.4} = $ **6.4 W/mm²**

Observation: The power density seems high enough for melting in the inner circle, but probably not sufficient in the ring that lies outside this inner circle.

28.3.2   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 the following equation [5]:

$$U_m = KT_{\mathrm{m}}^2 \qquad (28.2)$$

where $U_m = $ the unit energy for melting (i.e., the quantity of heat required to melt a unit volume of metal starting from room temperature), J/mm^3 (Btu/in^3); $T_m = $ melting point of the metal on an absolute temperature scale, °K (°R); and $K = $ constant whose value is 3.33×10^{-6} when the Kelvin scale is used (and $K = 1.467 \times 10^{-5}$ for the Rankine temperature scale). Absolute melting temperatures for selected metals are presented in Table 28.2.

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 28.8. 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:

$$H_w = f_1 f_2 H \qquad (28.3)$$

TABLE • 28.2 Melting temperatures on the absolute temperature scale for selected metals.

| Metal	Melting Temperature		Metal	Melting Temperature	
	°K[a]	°R[b]		°K[a]	°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].
[a]Kelvin scale = Centigrade (Celsius) temperature + 273.
[b]Rankine scale = Fahrenheit temperature + 460.

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
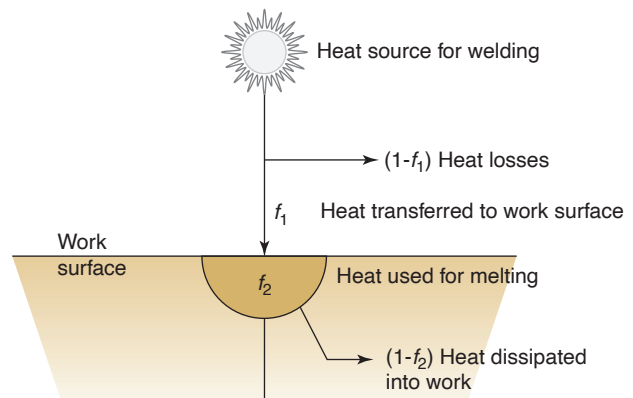
FIGURE 28.8 Heat transfer mechanisms in fusion welding.

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.

A balance equation between the energy input and the energy needed for welding can now be written:

$$H_w = U_m V \qquad (28.4)$$

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 Equation (28.4) as a rate balance equation:

$$R_{Hw} = U_m R_{WV} \qquad (28.5)$$

where R_{Hw} = rate of heat energy delivered to the operation for welding, J/s = W (Btu/min); and R_{WV} = 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

$$R_{Hw} = f_1 f_2 R_H = U_m A_w v \qquad (28.6)$$

where f_1 and f_2 are the heat transfer and melting factors; R_H = 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). Chapter 29 examines how the power density in Equation (28.1) and the input energy rate for Equation (28.6) are generated for some of the individual welding processes.

Example 28.2 Welding travel speed	The power source in a particular welding setup generates 3500 W that can be transferred to the work surface with a heat transfer factor = 0.7. The metal to be welded is low carbon steel, whose melting temperature, from Table 28.2, is 1760°K. The melting factor in the operation is 0.5. A continuous fillet weld is to be made with a cross-sectional area = 20 mm². Determine the travel speed at which the welding operation can be accomplished.

Solution: First find the unit energy required to melt the metal U_m from Equation (28.2).

$$U_m = 3.33(10^{-6}) \times 1760^2 = 10.3 \text{ J/mm}^3$$

Rearranging Equation (28.6) to solve for travel velocity, $v = \dfrac{f_1 f_2 R_H}{U_m A_w}$, and

solving for the conditions of the problem, $v = \dfrac{0.7(0.5)(3500)}{10.3(20)} = \textbf{5.95 mm/s}$

28.4   Features of a Fusion-Welded Joint

Most weld joints are fusion welded. As illustrated in the cross-sectional view of Figure 28.9(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 welding the mold is formed by the unmelted edges or surfaces of the components being welded. The significant 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 28.9(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. A detailed discussion of welding metallurgy is beyond the scope of this text, and interested readers can consult any of several references [1], [4], [5].

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
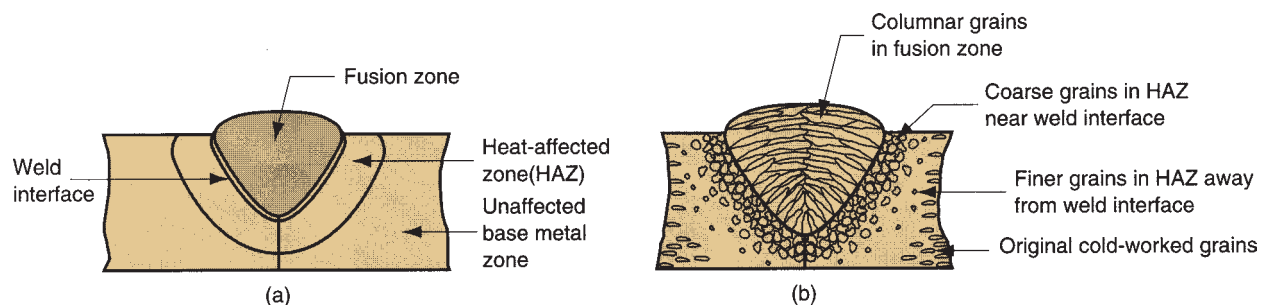
FIGURE 28.9   Cross section of a typical fusion-welded joint: (a) principal zones in the joint and (b) typical grain structure.

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.

References

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Review Questions

28.1 What are the advantages and disadvantages of welding compared to other types of assembly operations?

28.2 What were the two discoveries of Sir Humphrey Davy that led to the development of modern welding technology?

28.3 What is meant by the term faying surface?

28.4 Define the term fusion weld.

28.5 What is the fundamental difference between a fusion weld and a solid state weld?

28.6 What is an autogenous weld?

28.7 Discuss the reasons why most welding operations are inherently dangerous.

28.8 What is the difference between machine welding and automatic welding?

28.9 Name and sketch the five joint types.

28.10 Define and sketch a fillet weld.

28.11 Define and sketch a groove weld.

28.12 Why is a surfacing weld different from the other weld types?

28.13 Why is it desirable to use energy sources for welding that have high heat densities?

28.14 What is the unit melting energy in welding, and what are the factors on which it depends?

28.15 Define and distinguish the two terms heat transfer factor and melting factor in welding.

28.16 What is the heat-affected zone (HAZ) in a fusion weld?