29 Welding Processes

Chapter Contents

Welding processes divide into two major categories: (1) ***fusion welding***, in which coalescence is accomplished by melting the two part surfaces to be joined, in some cases adding filler metal to the joint; and (2) ***solid-state welding***, in which heat and/or pressure are used to achieve coalescence, but no melting of the base metals occurs and no filler metal is added.

Fusion welding is by far the more important category. It includes (1) arc welding, (2) resistance welding, (3) oxyfuel gas welding, and (4) other fusion welding processes—ones that cannot be classified as any of the first three types. Fusion welding processes are discussed in the first four sections of this chapter. Section 29.5 covers solid-state welding. And in the final three sections of the chapter, issues common to all welding operations are examined: weld quality, weldability, and design for welding.

29.1 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 (Section 25.3.4). A generic AW process is shown in Figure 29.1. 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 (10,000°F) 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 electrode is moved along the joint, the molten weld pool solidifies in its wake.

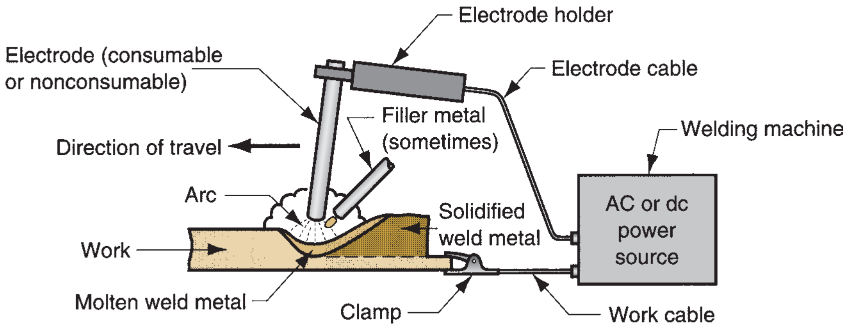

FIGURE 29.1 The basic configuration and electrical circuit of an arc-welding process.

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:

$$\text{Arc time} = (\text{time arc is on})/(\text{hours worked}) \tag{29.1}$$

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.

29.1.1 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. 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 the 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 (Section 28.3.2). Some representative values of f_1 for several AW processes are given in Table 29.1. Heat transfer factors are greater for AW processes that use

TABLE • 29.1 Heat transfer factors for several arc-welding processes.

Arc-Welding Process	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

Compiled from [1].

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 29.1 is gas tungsten arc welding, which uses a nonconsumable electrode. Melting factor f_2 (Section 28.3.2) further reduces the available heat for welding. The resulting power balance in arc welding is defined by

$$R_{Hw} = f_1 f_2 I E = U_m A_w v \tag{29.2}$$

where E = voltage, V; I = current, A; and the other terms were defined in Section 28.3.2. The units of R_{Hw} 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 = 1055 watts.

Example 29.1 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/mm^3. 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

$$P = IE = (300 \text{ A})(20 \text{ V}) = \mathbf{6000\ W}$$

(b) From Table 29.1, the heat transfer factor $f_1 = 0.7$. The rate of heat used for welding is given by

$$R_{Hw} = f_1 f_2 I E = (0.7)(0.5)(6000) = 2100 \text{ W} = \mathbf{2100\ J/s}$$

(c) The volume rate of metal welded is

$$R_{VW} = (2100 \text{ J/s})/(10 \text{ J/mm}^3) = \mathbf{210\ mm^3/s}$$

29.1.2 AW PROCESSES—CONSUMABLE ELECTRODES

A number of important arc-welding processes use consumable electrodes. These are discussed in this section. Symbols for the welding processes are those used by the American Welding Society.

Shielded Metal Arc Welding ***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 Figures 29.2 and 29.3. The welding stick (SMAW is sometimes called ***stick welding***) is typically 225 to 450 mm (9–18 in) long and 2.5 to 9.5 mm (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.

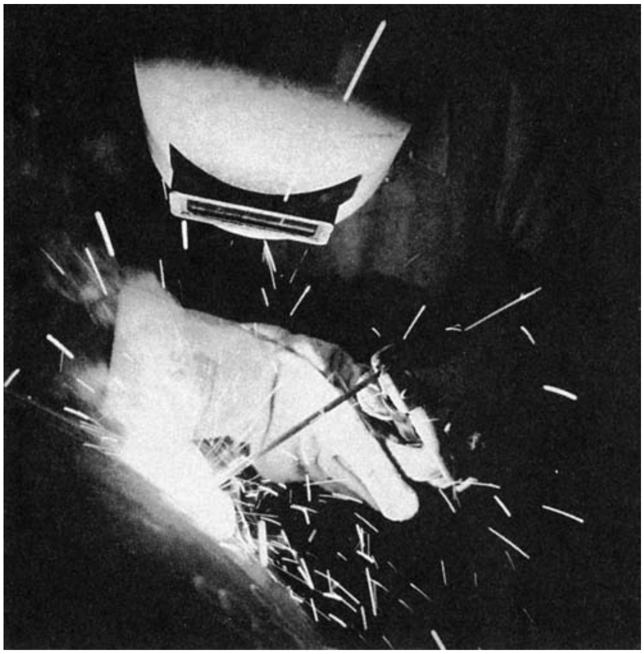

FIGURE 29.2 Shielded metal arc welding (stick welding) performed by a (human) welder. (Photo courtesy of Hobart Brothers Company.)

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

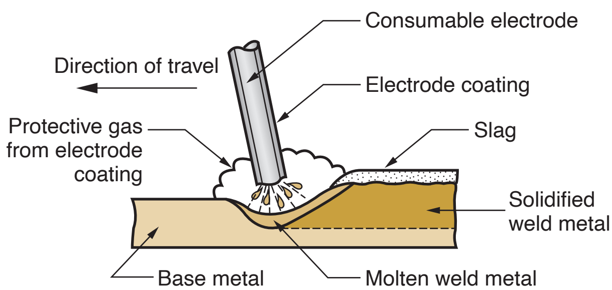

FIGURE 29.3 Shielded metal arc welding (SMAW).

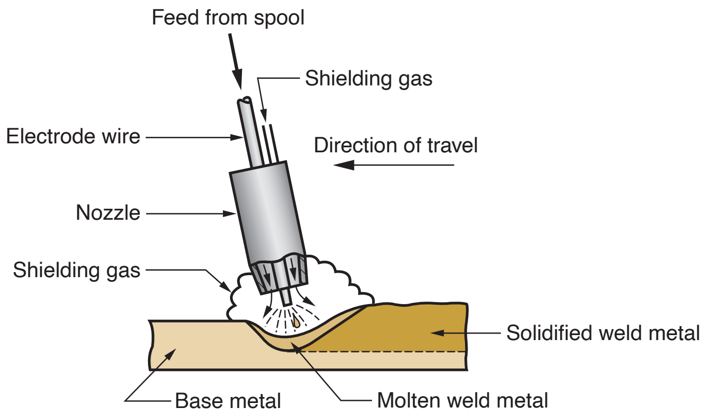

FIGURE 29.4
Gas metal arc welding (GMAW).

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.

Gas Metal Arc Welding ***Gas metal arc welding*** (GMAW) is an AW process in which the electrode is a consumable bare metal wire, and shielding is accomplished by flooding the arc with a gas. The bare wire is fed continuously and automatically from a spool through the welding gun, as illustrated in Figure 29.4. A welding gun is shown in Figure 29.5. Wire diameters ranging from 0.8 to 6.5 mm (1/32–1/4 in) are used in GMAW, the size depending on the thickness of the parts being joined and the desired deposition rate. Gases used for shielding include inert gases such as argon and helium, and active gases such as carbon dioxide. Selection of gases (and mixtures of gases) depends on the metal being welded, as well as other factors. Inert gases are used for welding aluminum alloys and stainless steels, while CO_2 is commonly used for welding low and medium carbon steels. The combination of bare electrode wire and shielding gases eliminates the slag covering on the weld bead and thus precludes the need for manual grinding and cleaning of the slag. The GMAW process is therefore ideal for making multiple welding passes on the same joint.

The various metals on which GMAW is used and the variations of the process itself have given rise to a variety of names for gas metal arc welding. When the process was first introduced in the late 1940s, it was applied to the welding of aluminum using inert gas (argon) for arc shielding. The name applied to this process was ***MIG welding*** (for ***m***etal ***i***nert ***g***as welding). When the same welding process was applied to steel, it was found that inert gases were expensive and CO_2 was used as a substitute. Hence the term ***CO_2 welding*** was applied. Refinements in GMAW for steel welding have led to the use of gas mixtures, including CO_2 and argon, and even oxygen and argon.

GMAW is widely used in fabrication operations in factories for welding a variety of ferrous and nonferrous metals. Because it uses continuous weld wire rather than welding sticks, it has a significant advantage over SMAW in terms of arc time when performed manually. For the same reason, it also lends itself to automation of arc welding. The electrode stubs remaining after stick welding also wastes filler metal,

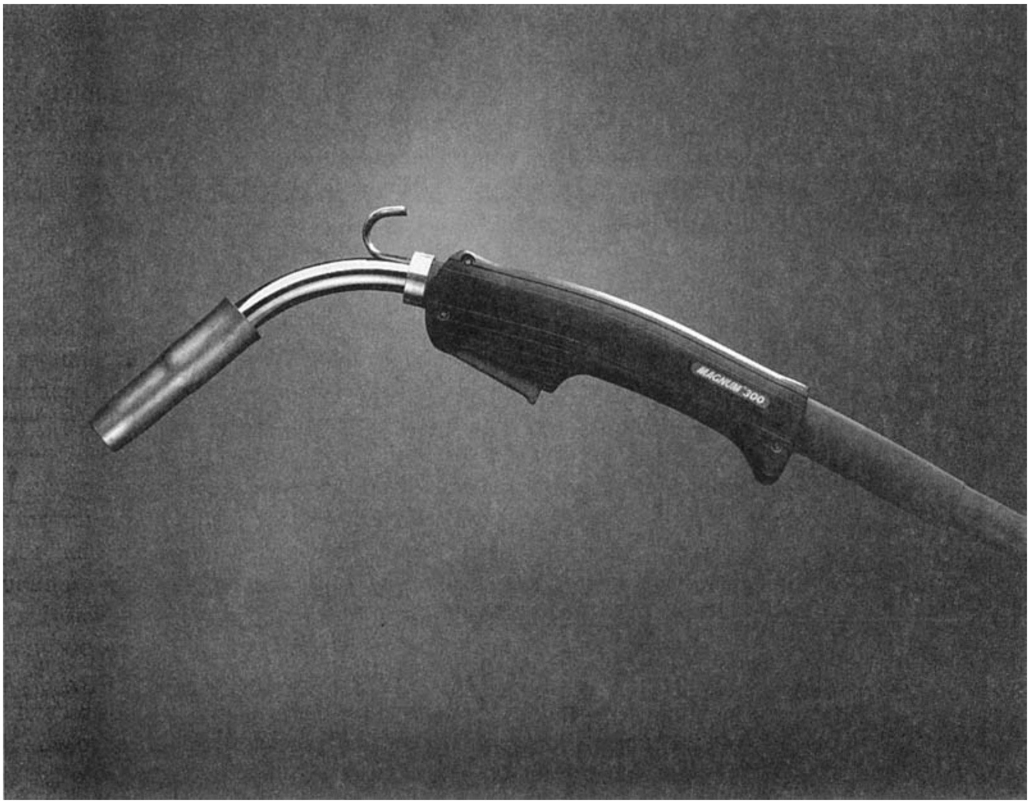

FIGURE 29.5 Welding gun for gas metal arc welding. (Courtesy of Lincoln Electric Company.)

so the utilization of electrode material is higher with GMAW. Other features of GMAW include elimination of slag removal (because no flux is used), higher deposition rates than SMAW, and good versatility.

Flux-Cored Arc Welding This arc-welding process was developed in the early 1950s as an adaptation of shielded metal arc welding to overcome the limitations imposed by the use of stick electrodes. ***Flux-cored arc welding*** (FCAW) is an arc-welding process in which the electrode is a continuous consumable tubing that contains flux and other ingredients in its core. Other ingredients may include deoxidizers and alloying elements. The tubular flux-cored "wire" is flexible and can therefore be supplied in the form of coils to be continuously fed through the arc-welding gun. There are two versions of FCAW: (1) self-shielded and (2) gas shielded. In the first version of FCAW to be developed, arc shielding was provided by a flux core, thus leading to the name ***self-shielded flux-cored arc welding***. The core in this form of FCAW includes not only fluxes but also ingredients that generate shielding gases for protecting the arc. The second version of FCAW, developed primarily for welding steels, obtains arc shielding from externally supplied gases, similar to gas metal arc welding. This version is called ***gas-shielded flux-cored arc welding***. Because it utilizes an electrode containing its own flux together with separate shielding gases, it might be considered a hybrid of SMAW and GMAW. Shielding gases typically employed are carbon dioxide for mild steels or mixtures of argon and carbon dioxide

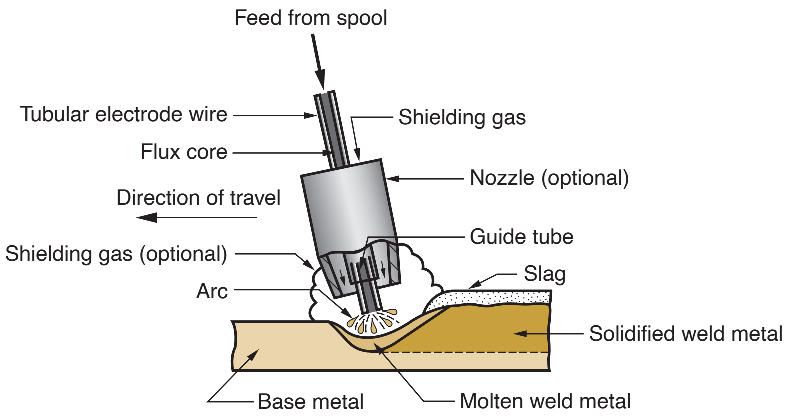

FIGURE 29.6 Flux-cored arc welding. The presence or absence of externally supplied shielding gas distinguishes the two types: (1) self-shielded, in which the core provides the ingredients for shielding; and (2) gas shielded, in which external shielding gases are supplied.

for stainless steels. Figure 29.6 illustrates the FCAW process, with the gas (optional) distinguishing between the two types.

FCAW has advantages similar to GMAW, due to continuous feeding of the electrode. It is used primarily for welding steels and stainless steels over a wide stock thickness range. It is noted for its capability to produce very-high-quality weld joints that are smooth and uniform.

Electrogas Welding Electrogas welding (EGW) is an AW process that uses a continuous consumable electrode (either flux-cored wire or bare wire with externally supplied shielding gases) and molding shoes to contain the molten metal. The process is primarily applied to vertical butt welding, as pictured in Figure 29.7. When the flux-cored electrode wire is employed, no external gases are supplied, and the process can be considered a special application of self-shielded FCAW. When a bare electrode wire is used with shielding gases from an external source, it is considered a special case of GMAW. The molding shoes are water cooled to prevent their being added to the weld pool. Together with the edges of the parts being welded, the shoes form a container, almost like a mold cavity, into which the molten metal from the electrode and base parts is gradually added. The process is performed automatically, with a moving weld head travelling vertically upward to fill the cavity in a single pass.

Principal applications of electrogas welding are steels (low-and medium-carbon, low-alloy, and certain stainless steels) in the construction of large storage tanks and

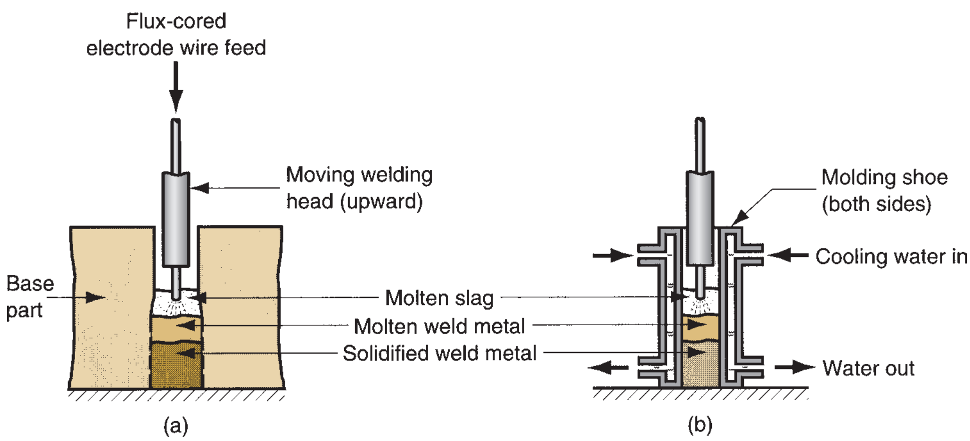

FIGURE 29.7 Electrogas welding using flux-cored electrode wire: (a) front view with molding shoe removed for clarity, and (b) side view showing molding shoes on both sides.

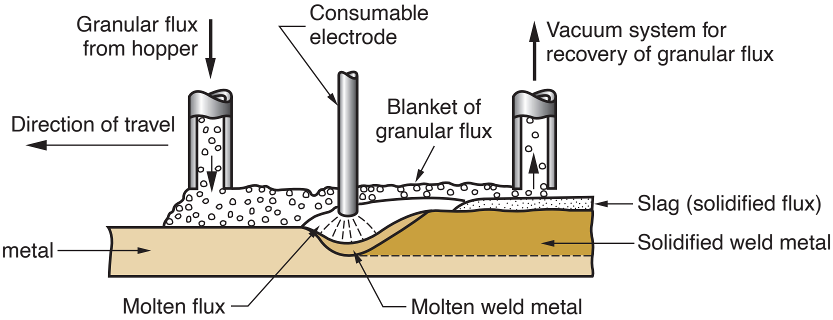

FIGURE 29.8 Submerged arc welding (SAW).

in shipbuilding. Stock thicknesses from 12 to 75 mm (0.5–3.0 in) are within the capacity of EGW. In addition to butt welding, it can also be used for fillet and groove welds, always in a vertical orientation. Specially designed molding shoes must sometimes be fabricated for the joint shapes involved.

Submerged Arc Welding This process, developed during the 1930s, was one of the first AW processes to be automated. ***Submerged arc welding*** (SAW) is an arc-welding process that uses a continuous, consumable bare wire electrode, and arc shielding is provided by a cover of granular flux. The electrode wire is fed automatically from a coil into the arc. The flux is introduced into the joint slightly ahead of the weld arc by gravity from a hopper, as shown in Figure 29.8. The blanket of granular flux completely submerges the welding operation, preventing sparks, spatter, and radiation that are so hazardous in other AW processes. Thus, the welding operator in SAW need not wear the somewhat cumbersome face shield required in the other operations (safety glasses and protective gloves, of course, are required). The portion of the flux closest to the arc is melted, mixing with the molten weld metal to remove impurities and then solidifying on top of the weld joint to form a glass-like slag. The slag and unfused flux granules on top provide good protection from the atmosphere and good thermal insulation for the weld area, resulting in relatively slow cooling and a high-quality weld joint, noted for toughness and ductility. As depicted in the sketch, the unfused flux remaining after welding can be recovered and reused. The solid slag covering the weld must be chipped away, usually by manual means.

Submerged arc welding is widely used in steel fabrication for structural shapes (e.g., welded I-beams); longitudinal and circumferential seams for large diameter pipes, tanks, and pressure vessels; and welded components for heavy machinery. In these kinds of applications, steel plates of 25-mm (1.0-in) thickness and heavier are routinely welded by this process. Low-carbon, low-alloy, and stainless steels can be readily welded by SAW; but not high-carbon steels, tool steels, and most nonferrous metals. Because of the gravity feed of the granular flux, the parts must always be in a horizontal orientation, and a backup plate is often required beneath the joint during the welding operation.

29.1.3 AW PROCESSES—NONCONSUMABLE ELECTRODES

The AW processes discussed above use consumable electrodes. Gas tungsten arc welding, plasma arc welding, and several other processes use nonconsumable electrodes.

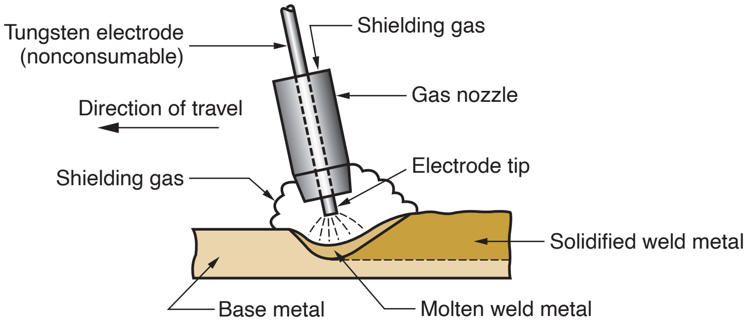

FIGURE 29.9 Gas tungsten arc welding (GTAW).

Gas Tungsten Arc Welding Gas tungsten arc welding (GTAW) is an AW process that uses a nonconsumable tungsten electrode and an inert gas for arc shielding. The term ***TIG welding*** (***t***ungsten ***i***nert ***g***as welding) is often applied to this process (in Europe, ***WIG welding*** is the term—the chemical symbol for tungsten is W, for Wolfram). GTAW can be implemented with or without a filler metal. Figure 29.9 illustrates the latter case. When a filler metal is used, it is added to the weld pool from a separate rod or wire, being melted by the heat of the arc rather than transferred across the arc as in the consumable electrode AW processes. Tungsten is a good electrode material due to its high melting point of 3410°C (6170°F). Typical shielding gases include argon, helium, or a mixture of these gas elements.

GTAW is applicable to nearly all metals in a wide range of stock thicknesses. It can also be used for joining various combinations of dissimilar metals. Its most common applications are for aluminum and stainless steel. Cast irons, wrought irons, and of course tungsten are difficult to weld by GTAW. In steel welding applications, GTAW is generally slower and more costly than the consumable electrode AW processes, except when thin sections are involved and very-high-quality welds are required. When thin sheets are TIG welded to close tolerances, filler metal is usually not added. The process can be performed manually or by machine and automated methods for all joint types. Advantages of GTAW in the applications to which it is suited include high-quality welds, no weld spatter because no filler metal is transferred across the arc, and little or no postweld cleaning because no flux is used.

Plasma Arc Welding Plasma arc welding (PAW) is a special form of gas tungsten arc welding in which a constricted plasma arc is directed at the weld area. In PAW, a tungsten electrode is contained in a specially designed nozzle that focuses a high-velocity stream of inert gas (e.g., argon or argon–hydrogen mixtures) into the region of the arc to form a high-velocity, intensely hot plasma arc stream, as in Figure 29.10. Argon, argon–hydrogen, and helium are also used as the arc-shielding gases.

Temperatures in plasma arc welding reach 17,000°C (30,000°F) or greater, hot enough to melt any known metal. The reason why temperatures are so high in PAW (significantly higher than those in GTAW) derives from the constriction of the arc. Although the typical power levels used in PAW are below those used in GTAW, the power is highly concentrated to produce a plasma jet of small diameter and very high power density.

Plasma arc welding was introduced around 1960 but was slow to catch on. In recent years its use is increasing as a substitute for GTAW in applications such as automobile subassemblies, metal cabinets, door and window frames, and home appliances. Owing to the special features of PAW, its advantages in these applications include good arc

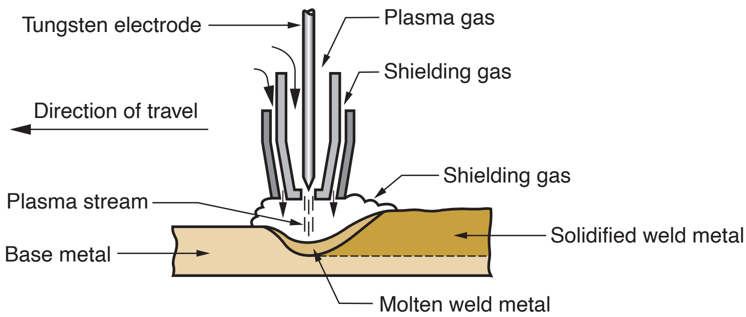

FIGURE 29.10 Plasma arc welding (PAW).

stability, better penetration control than most other AW processes, high travel speeds, and excellent weld quality. The process can be used to weld almost any metal, including tungsten. Difficult-to-weld metals with PAW include bronze, cast irons, lead, and magnesium. Other limitations include high equipment cost and larger torch size than other AW operations, which tends to restrict access in some joint configurations.

Other Arc-Welding and Related Processes The preceding AW processes are the most important commercially. There are several others that should be mentioned, which are special cases or variations of the principal AW processes.

Carbon arc welding (CAW) is an arc-welding process in which a nonconsumable carbon (graphite) electrode is used. It has historical importance because it was the first arc-welding process to be developed, but its commercial importance today is practically nil. The carbon arc process is used as a heat source for brazing and for repairing iron castings. It can also be used in some applications for depositing wear-resistant materials on surfaces. Graphite electrodes for welding have been largely superseded by tungsten (in GTAW and PAW).

Stud welding (SW) is a specialized AW process for joining studs or similar components to base parts. A typical SW operation is illustrated in Figure 29.11, in which shielding is obtained by the use of a ceramic ferrule. To begin with, the stud is chucked in a special weld gun that automatically controls the timing and power parameters of the steps shown in the sequence. The worker must only position the gun at the proper location against the base work part to which the stud will be attached and pull the trigger. SW applications include threaded fasteners for attaching handles to

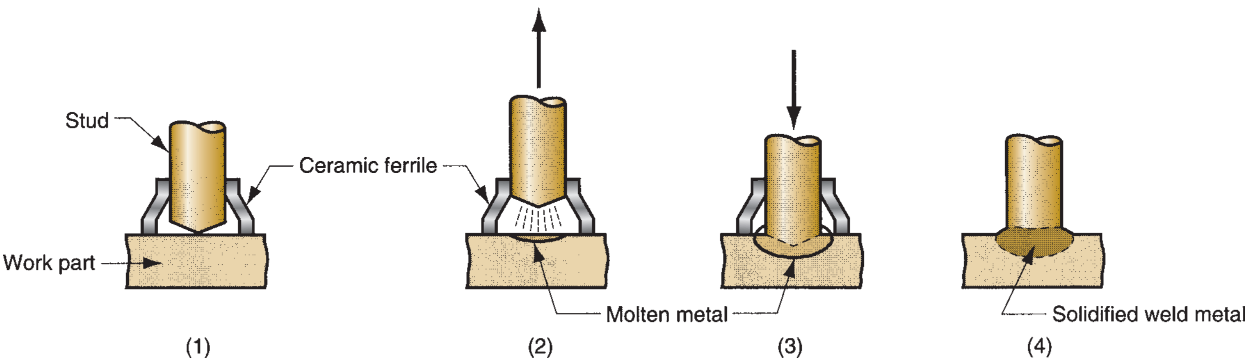

FIGURE 29.11 Stud arc welding (SW): (1) stud is positioned; (2) current flows from the gun, and stud is pulled from base to establish arc and create a molten pool; (3) stud is plunged into molten pool; and (4) ceramic ferrule is removed after solidification.

cookware, heat radiation fins on machinery, and similar assembly situations. In high-production operations, stud welding usually has advantages over rivets, manually arc-welded attachments, and drilled and tapped holes.

29.2 Resistance Welding

Resistance welding (RW) is a group of fusion-welding processes that uses a combination of heat and pressure to accomplish coalescence, the heat being generated by electrical resistance to current flow at the junction to be welded. The principal components in resistance welding are shown in Figure 29.12 for a resistance spot-welding operation, the most widely used process in the group. The components include work parts to be welded (usually sheet metal parts), two opposing electrodes, a means of applying pressure to squeeze the parts between the electrodes, and an AC power supply from which a controlled current can be applied. The operation results in a fused zone between the two parts, called a ***weld nugget*** in spot welding.

By comparison to arc welding, resistance welding uses no shielding gases, flux, or filler metal; and the electrodes that conduct electrical power to the process are nonconsumable. RW is classified as fusion welding because the applied heat almost always causes melting of the faying surfaces. However, there are exceptions. Some welding operations based on resistance heating use temperatures below the melting points of the base metals, so fusion does not occur.

29.2.1 POWER SOURCE IN RESISTANCE WELDING

The heat energy supplied to the welding operation depends on current flow, resistance of the circuit, and length of time the current is applied. This can be expressed by the equation

$$H = I^2 Rt \tag{29.3}$$

where H = heat generated, J (to convert to Btu divide by 1055); I = current, A; R = electrical resistance, Ω; and t = time, s.

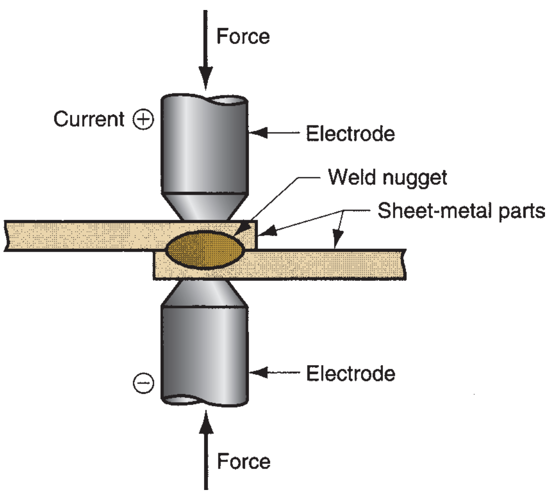

FIGURE 29.12 Resistance welding (RW), showing the components in spot welding, the predominant process in the RW group.

The current used in resistance welding operations is very high (5000–20,000 A, typically), although voltage is relatively low (usually below 10 V). The duration t of the current is short in most processes, perhaps lasting 0.1 to 0.4 s in a typical spot-welding operation.

The reason why such a high current is used in RW is because (1) the squared term in Equation (29.3) amplifies the effect of current, and (2) the resistance is very low (around 0.0001 Ω). Resistance in the welding circuit is the sum of (1) resistance of the electrodes, (2) resistances of the work parts, (3) contact resistances between electrodes and work parts, and (4) contact resistance of the faying surfaces. Thus, heat is generated in all of these regions of electrical resistance. The ideal situation is for the faying surfaces to be the largest resistance in the sum, because this is the desired location of the weld. The resistance of the electrodes is minimized by using metals with very low resistivities, such as copper. Also, the electrodes are often water cooled to dissipate the heat that is generated there. The work part resistances are a function of the resistivities of the base metals and the part thicknesses. The contact resistances between the electrodes and the parts are determined by the contact areas (i.e., size and shape of the electrode) and the condition of the surfaces (e.g., cleanliness of the work surfaces and scale on the electrode). Finally, the resistance at the faying surfaces depends on surface finish, cleanliness, contact area, and pressure. No paint, oil, dirt, or other contaminants should be present to separate the contacting surfaces.

Example 29.2 Resistance welding

A resistance spot-welding operation performed on two pieces of 2.5-mm-thick sheet steel uses 12,000 amps for a 0.20-s duration. The electrodes are 6 mm in diameter at the contacting surfaces. Resistance is assumed to be 0.0001 Ω, and the resulting weld nugget 6 mm in diameter and averages 3 mm in thickness. The unit melting energy for the metal $U_m = 12.0$ J/mm^3. What portion of the heat generated was used to form the weld nugget, and what portion was dissipated into the work metal, electrodes, and surrounding air?

Solution: The heat generated in the operation is given by Equation (29.3) as.

$$H = (12{,}000)^2(0.0001)(0.2) = 2880 \text{ J}$$

The volume of the weld nugget (assumed disc-shaped) is $v = 3.0\dfrac{\pi(6)^2}{4} = 84.8$ mm^3.

The heat required to melt this volume of metal is $Hw = 84.8(12.0) = \mathbf{1018\ J}$. The remaining heat, 2880–1018 = **1862 J** (64.7% of the total), is lost into the work metal, electrodes, and surrounding air. In effect, this loss represents the combined effect of the heat transfer factor f_1 and melting factor f_2 (Section 28.3.2).

Success in resistance welding depends on pressure as well as heat. The principal functions of pressure in RW are to (1) force contact between the electrodes and the work parts and between the two work surfaces prior to applying current, and (2) press the faying surfaces together to accomplish coalescence when the proper welding temperature has been reached.

General advantages of resistance welding include (1) no filler metal is required, (2) high production rates are possible, (3) lends itself to mechanization and automation, (4) operator skill level is lower than that required for arc welding, and

(5) good repeatability and reliability. Drawbacks are (1) equipment cost is high—usually much higher than most arc-welding operations, and (2) types of joints that can be welded are limited to lap joints for most RW processes.

29.2.2 RESISTANCE-WELDING PROCESSES

The resistance-welding processes of most commercial importance are spot, seam, and projection welding.

Resistance Spot Welding Resistance spot welding is by far the predominant process in this group. It is widely used in mass production of automobiles, appliances, metal furniture, and other products made of sheet metal. If one considers that a typical car body has approximately 10,000 individual spot welds, and that the annual production of automobiles throughout the world is measured in tens of millions of units, the economic importance of resistance spot welding can be appreciated.

Resistance spot welding (RSW) is an RW process in which fusion of the faying surfaces of a lap joint is achieved at one location by opposing electrodes. The process is used to join sheet-metal parts of thickness 3 mm (0.125 in) or less, using a series of spot welds, in situations where an airtight assembly is not required. The size and shape of the weld spot is determined by the electrode tip, the most common electrode shape being round, but hexagonal, square, and other shapes are also used. The resulting weld nugget is typically 5 to 10 mm (0.2–0.4 in) in diameter, with a heat-affected zone extending slightly beyond the nugget into the base metals. If the weld is made properly, its strength will be comparable to that of the surrounding metal. The steps in a spot welding cycle are depicted in Figure 29.13.

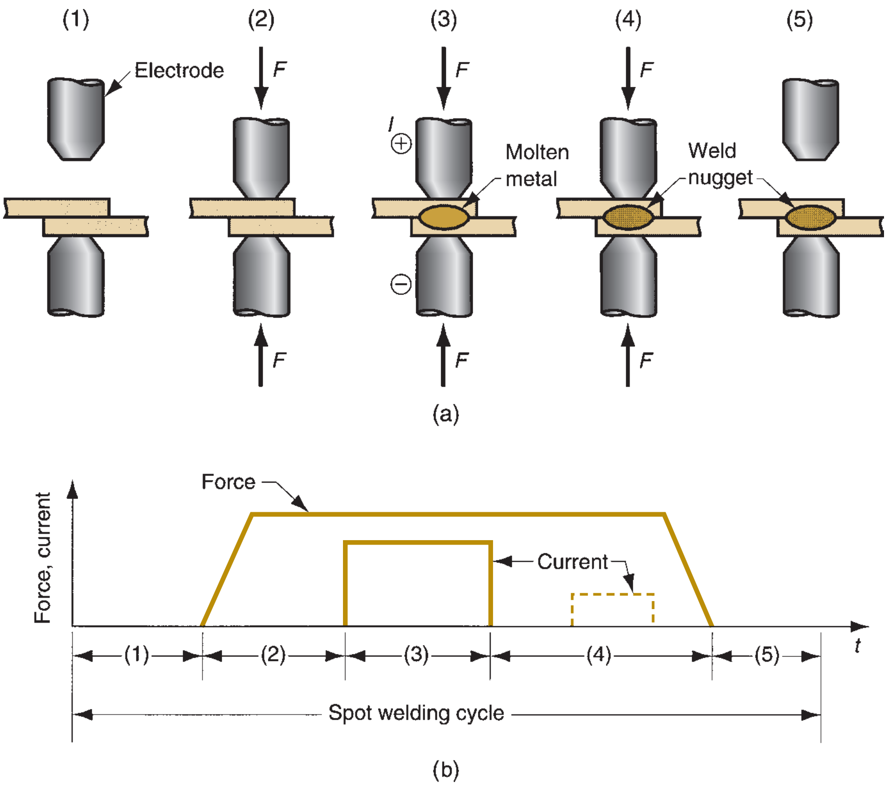

FIGURE 29.13 (a) Steps in a resistance spot-welding (RSW) cycle, and (b) plot of squeezing force and current during cycle. The sequence is: (1) parts inserted between open electrodes, (2) electrodes close and force is applied, (3) weld time—current is switched on, (4) current is turned off but force is maintained or increased (a reduced current is sometimes applied near the end of this step for stress relief in the weld region), and (5) electrodes are opened, and the welded assembly is removed.

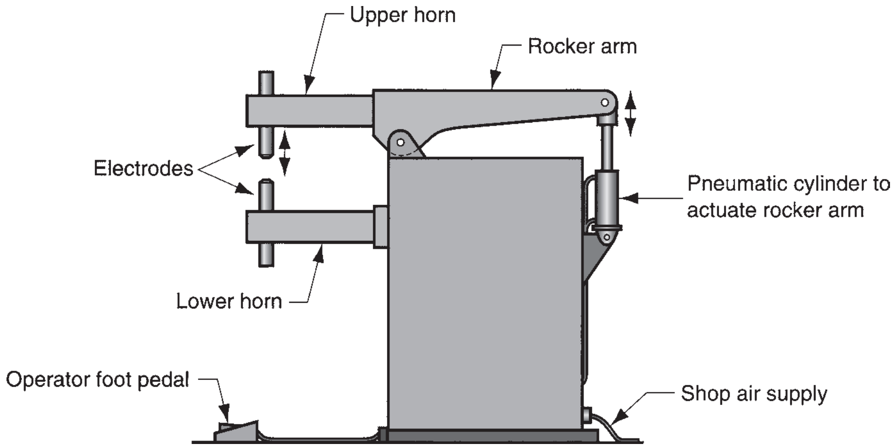

FIGURE 29.14 Rocker-arm spot-welding machine.

Materials used for RSW electrodes consist of two main groups: (1) copper-based alloys and (2) refractory metal compositions such as copper and tungsten combinations. The second group is noted for superior wear resistance. As in most manufacturing processes, the tooling in spot welding gradually wears out as it is used. Whenever practical, the electrodes are designed with internal passageways for water cooling.

Because of its widespread industrial use, various machines and methods are available to perform spot-welding operations. The equipment includes rocker-arm and press-type spot-welding machines, and portable spot-welding guns. ***Rocker-arm spot welders***, shown in Figure 29.14, have a stationary lower electrode and a movable upper electrode that can be raised and lowered for loading and unloading the work. The upper electrode is mounted on a rocker arm (hence the name) whose movement is controlled by a foot pedal operated by the worker. Modern machines can be programmed to control force and current during the weld cycle.

Press-type spot welders are intended for larger work. The upper electrode has a straight-line motion provided by a vertical press that is pneumatically or hydraulically powered. The press action permits larger forces to be applied, and the controls usually permit programming of complex weld cycles.

The previous two machine types are both stationary spot welders, in which the work is brought to the machine. For large, heavy work it is difficult to move and position the part into stationary machines. For these cases, ***portable spot-welding guns*** are available in various sizes and configurations. These devices consist of two opposing electrodes contained in a pincer mechanism. Each unit is light weight so that it can be held and manipulated by a human worker or an industrial robot. The gun is connected to its own power and control source by means of flexible electrical cables and air hoses. Water cooling for the electrodes, if needed, can also be provided through a water hose. Portable spot-welding guns are widely used in automobile final assembly plants to spot weld car bodies. Some of these guns are operated by people, but industrial robots have become the preferred technology, illustrated in Figure 38.16.

Resistance Seam Welding In resistance seam welding (RSEW), the stick-shaped electrodes in spot welding are replaced by rotating wheels, as shown in Figure 29.15, and a series of overlapping spot welds are made along the lap joint. The process is capable of producing air-tight joints, and its industrial applications include the production of gasoline tanks, automobile mufflers, and various other fabricated

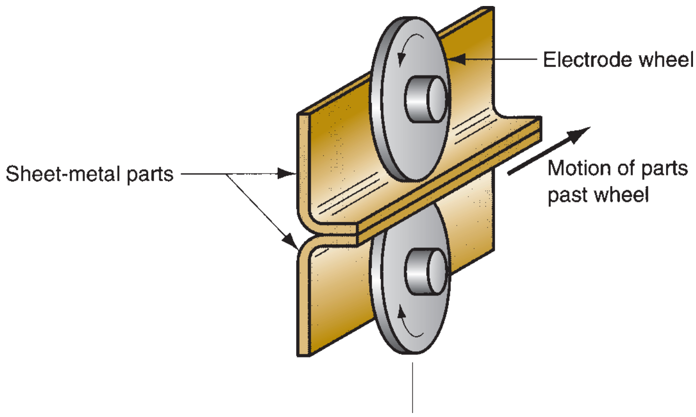

FIGURE 29.15 Resistance seam welding (RSEW).

sheet metal containers. Technically, RSEW is the same as spot welding, except that the wheel electrodes introduce certain complexities. Because the operation is usually carried out continuously, rather than discretely, the seams should be along a straight or uniformly curved line. Sharp corners and similar discontinuities are difficult to deal with. Also, warping of the parts becomes more of a factor in resistance seam welding, and fixtures are required to hold the work in position and minimize distortion.

The spacing between the weld nuggets in resistance seam welding depends on the motion of the electrode wheels relative to the application of the weld current. In the usual method of operation, called ***continuous motion welding***, the wheel is rotated continuously at a constant velocity, and current is turned on at timing intervals consistent with the desired spacing between spot welds along the seam. Frequency of the current discharges is normally set so that overlapping weld spots are produced. But if the frequency is reduced sufficiently, then there will be spaces between the weld spots, and this method is termed ***roll spot welding***. In another variation, the welding current remains on at a constant level (rather than being pulsed) so that a truly continuous welding seam is produced. These variations are depicted in Figure 29.16.

An alternative to continuous motion welding is ***intermittent motion welding***, in which the electrode wheel is periodically stopped to make the spot weld. The amount of wheel rotation between stops determines the distance between weld spots along the seam, yielding patterns similar to (a) and (b) in Figure 29.16.

Seam-welding machines are similar to press-type spot welders except that electrode wheels are used rather than the usual stick-shaped electrodes. Cooling of the work and wheels is often necessary in RSEW, and this is accomplished by directing water at the top and underside of the work part surfaces near the electrode wheels.

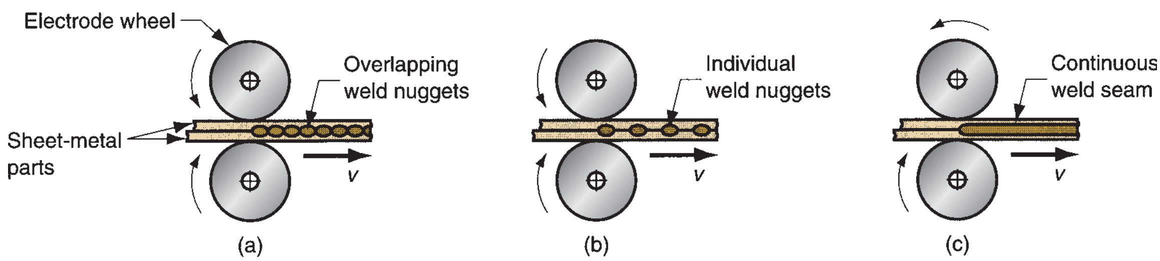

FIGURE 29.16 Different types of seams produced by electrode wheels: (a) conventional resistance seam welding, in which overlapping spots are produced; (b) roll spot welding; and (c) continuous resistance seam.

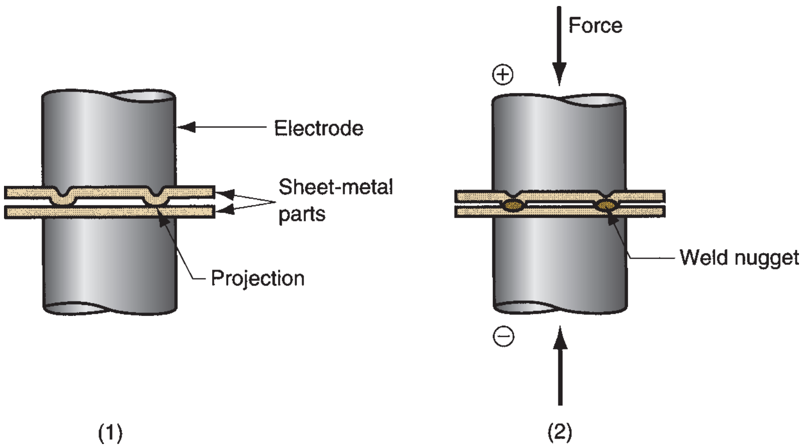

FIGURE 29.17 Resistance projection welding (RPW): (1) at start of operation, contact between parts is at projections; and (2) when current is applied, weld nuggets similar to those in spot welding are formed at the projections.

Resistance Projection Welding Resistance projection welding (RPW) is an RW process in which coalescence occurs at one or more relatively small contact points on the parts. These contact points are determined by the design of the parts to be joined, and may consist of projections, embossments, or localized intersections of the parts. A typical case in which two sheet-metal parts are welded together is described in Figure 29.17. The part on top has been fabricated with two embossed points to contact the other part at the start of the process. It might be argued that the embossing operation increases the cost of the part, but this increase may be more than offset by savings in welding cost.

There are variations of resistance projection welding, two of which are shown in Figure 29.18. In one variation, fasteners with machined or formed projections can be permanently joined to sheet or plate by RPW, facilitating subsequent assembly operations. Another variation, called ***cross-wire welding***, is used to fabricate welded wire products such as wire fence, shopping carts, and stove grills. In this process, the contacting surfaces of the round wires serve as the projections to localize the resistance heat for welding.

Other Resistance-Welding Operations In addition to the principal RW processes described above, several additional processes in this group should be identified: flash, upset, percussion, and high-frequency resistance welding.

In ***flash welding*** (FW), normally used for butt joints, the two surfaces to be joined are brought into contact or near contact and electric current is applied to

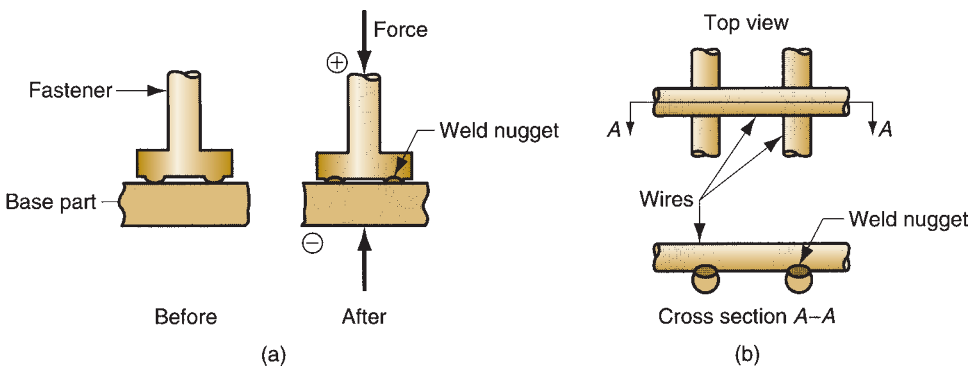

FIGURE 29.18 Variations of resistance projection welding: (a) welding of a machined or formed fastener onto a sheet-metal part; and (b) cross-wire welding.

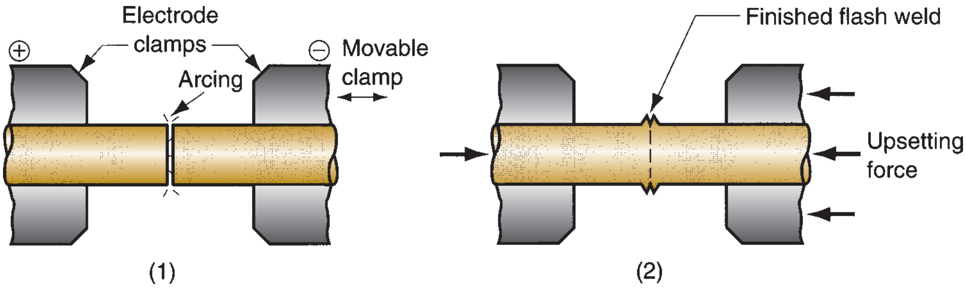

FIGURE 29.19 Flash welding (FW): (1) heating by electrical resistance; and (2) upsetting—parts are forced together.

heat the surfaces to the melting point, after which the surfaces are forced together to form the weld. The two steps are outlined in Figure 29.19. In addition to resistance heating, some arcing occurs (called ***flashing***, hence the name of the welding process), depending on the extent of contact between the faying surfaces, so flash welding is sometimes classified in the arc welding group. Current is usually stopped during upsetting. Some metal, as well as contaminants on the surfaces, is squeezed out of the joint and must be subsequently machined to provide a joint of uniform size.

Applications of flash welding include butt welding of steel strips in rolling-mill operations, joining ends of wire in wire drawing, and welding of tubular parts. The ends to be joined must have the same cross sections. For these kinds of high-production applications, flash welding is fast and economical, but the equipment is expensive.

Upset welding (UW) is similar to flash welding except that in UW the faying surfaces are pressed together during heating and upsetting. In flash welding, the heating and pressing steps are separated during the cycle. Heating in UW is accomplished entirely by electrical resistance at the contacting surfaces; no arcing occurs. When the faying surfaces have been heated to a suitable temperature below the melting point, the force pressing the parts together is increased to cause upsetting and coalescence in the contact region. Thus, upset welding is not a fusion-welding process in the same sense as the other welding processes discussed. Applications of UW are similar to those of flash welding: joining ends of wire, pipes, tubes, and so on.

Percussion welding (PEW) is also similar to flash welding, except that the duration of the weld cycle is extremely short, typically lasting only 1 to 10 ms. Fast heating is accomplished by rapid discharge of electrical energy between the two surfaces to be joined, followed immediately by percussion of one part against the other to form the weld. The heating is very localized, making this process attractive for electronic applications in which the dimensions are very small and nearby components may be sensitive to heat.

High-frequency resistance welding (HFRW) is a resistance-welding process in which a high-frequency alternating current is used for heating, followed by the rapid application of an upsetting force to cause coalescence, as in Figure 29.20(a). The frequencies are 10 to 500 kHz, and the electrodes make contact with the work in the immediate vicinity of the weld joint. In a variation of the process, called ***high-frequency induction welding*** (HFIW), the heating current is induced in the parts by a high-frequency induction coil, as in Figure 29.20(b). The coil does not make physical contact with the work. The principal applications of both HFRW and HFIW are continuous butt welding of the longitudinal seams of metal pipes and tubes.

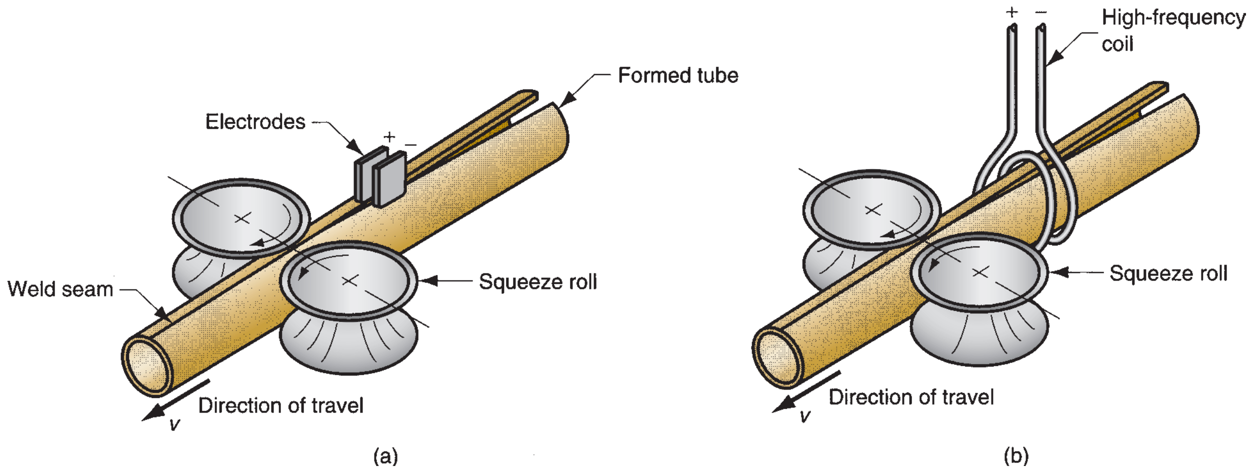

FIGURE 29.20 Welding of tube seams by: (a) high-frequency resistance welding, and (b) high-frequency induction welding.

29.3 Oxyfuel Gas Welding

Oxyfuel gas welding (OFW) is the term used to describe the group of FW operations that burn various fuels mixed with oxygen to perform welding. The OFW processes employ several types of gases, which is the primary distinction among the members of this group. Oxyfuel gas is also commonly used in cutting torches to cut and separate metal plates and other parts (Section 25.3.5). The most important OFW process is oxyacetylene welding.

29.3.1 OXYACETYLENE WELDING

Oxyacetylene welding (OAW) is a fusion-welding process performed by a high-temperature flame from combustion of acetylene and oxygen. The flame is directed by a welding torch. A filler metal is sometimes added, and pressure is occasionally applied in OAW between the contacting part surfaces. A typical OAW operation is sketched in Figure 29.21. When filler metal is used, it is typically in the form of a rod with diameters ranging from 1.6 to 9.5 mm (1/16–3/8 in). Composition of the filler

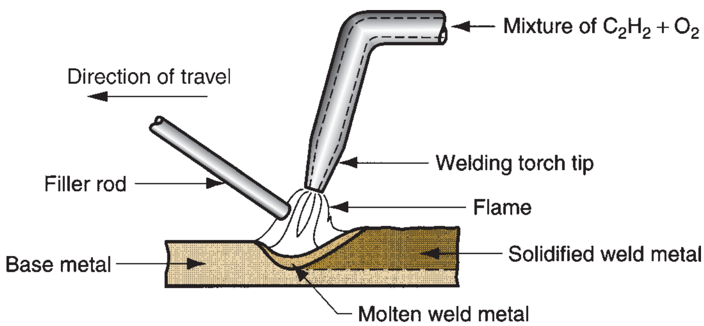

FIGURE 29.21 A typical oxyacetylene welding operation (OAW).

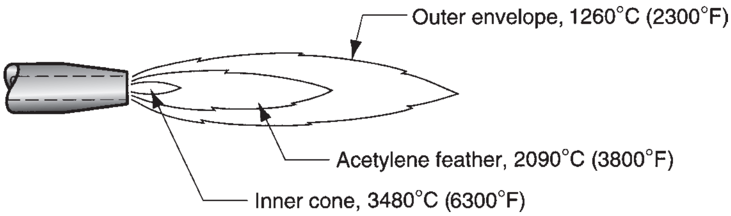

FIGURE 29.22 The neutral flame from an oxyacetylene torch, indicating temperatures achieved.

must be similar to that of the base metals. The filler is often coated with a ***flux*** that helps to clean the surfaces and prevent oxidation, thus creating a better weld joint.

Acetylene (C_2H_2) is the most popular fuel among the OFW group because it is capable of higher temperatures than any of the others—up to 3480°C (6300°F). The flame in OAW is produced by the chemical reaction of acetylene and oxygen in two stages. The first stage is defined by the reaction

$$C_2H_2 + O_2 \rightarrow 2CO + H_2 + \text{heat} \tag{29.4a}$$

the products of which are both combustible, which leads to the second-stage reaction

$$2CO + H_2 + 1.5O_2 \rightarrow 2CO_2 + H_2O + \text{heat} \tag{29.4b}$$

The two stages of combustion are visible in the oxyacetylene flame emitted from the torch. When the mixture of acetylene and oxygen is in the ratio 1:1, as described in Equation (29.4), the resulting ***neutral flame*** is shown in Figure 29.22. The first-stage reaction is seen as the inner cone of the flame (which is bright white), while the second-stage reaction is exhibited by the outer envelope (which is nearly colorless but with tinges ranging from blue to orange). The maximum temperature of the flame is reached at the tip of the inner cone; the second-stage temperatures are somewhat below those of the inner cone. During welding, the outer envelope spreads out and covers the work surfaces being joined, thus shielding them from the surrounding atmosphere.

Total heat liberated during the two stages of combustion is 55×10^6 J/m^3 (1470 Btu/ft^3) of acetylene. However, because of the temperature distribution in the flame, the way in which the flame spreads over the work surface, and losses to the air, power densities and heat transfer factors in oxyacetylene welding are relatively low; $f_1 = 0.10$ to 0.30.

Example 29.3 Heat generation in oxyacetylene welding

An oxyacetylene torch supplies 0.3 m^3 of acetylene per hour and an equal volume rate of oxygen for an OAW operation on 4.5-mm-thick steel. Heat generated by combustion is transferred to the work surface with a heat transfer factor $f_1 = 0.20$. If 75% of the heat from the flame is concentrated in a circular area on the work surface that is 9.0 mm in diameter, find (a) rate of heat liberated during combustion, (b) rate of heat transferred to the work surface, and (c) average power density in the circular area.

Solution: (a) The rate of heat generated by the torch is the product of the volume rate of acetylene times the heat of combustion:

$$R_H = (0.3 \text{ m}^3/\text{hr})(55 \times 10^6 \text{ J/m}^3) = 16.5 \times 10^6 \text{ J/hr or } \mathbf{4583\ J/s}$$

(b) With a heat transfer factor $f_1 = 0.20$, the rate of heat received at the work surface is

$$f_1 R_H = 0.20(4583) = \mathbf{917\ J/s}$$

(c) The area of the circle in which 75% of the heat of the flame is concentrated is

$$A = \frac{\pi(9)^2}{4} = 63.6\ \text{mm}^2.$$

The power density in the circle is found by dividing the available heat by the area of the circle:

$$PD = \frac{0.75(917)}{63.6} = \mathbf{10.8\ W/mm^2}$$

The combination of acetylene and oxygen is highly flammable, and the environment in which OAW is performed is therefore hazardous. Some of the dangers relate specifically to the acetylene. Pure C_2H_2 is a colorless, odorless gas. For safety reasons, commercial acetylene is processed to have a characteristic garlic odor. One of the physical limitations of the gas is that it is unstable at pressures much above 1 atm (0.1 MPa or 15 lb/in^2). Accordingly, acetylene storage cylinders are packed with a porous filler material (such as asbestos, balsa wood, and other materials) saturated with acetone (CH_3COCH_3). Acetylene dissolves in liquid acetone; in fact, acetone dissolves about 25 times its own volume of acetylene, thus providing a relatively safe means of storing this welding gas. The welder wears eye and skin protection (goggles, gloves, and protective clothing) as an additional safety precaution, and different screw threads are standard on the acetylene and oxygen cylinders and hoses to avoid accidental connection of the wrong gases. Proper maintenance of the equipment is imperative. OAW equipment is relatively inexpensive and portable. It is therefore an economical, versatile process that is well suited to low-quantity production and repair jobs. It is rarely used to weld sheet and plate stock thicker than 6.4 mm (1/4 in) because of the advantages of arc welding in such applications. Although OAW can be mechanized, it is usually performed manually and is hence dependent on the skill of the welder to produce a high-quality weld joint.

29.3.2 ALTERNATIVE GASES FOR OXYFUEL WELDING

Several members of the OFW group are based on gases other than acetylene. Most of the alternative fuels are listed in Table 29.2, together with their burning temperatures and combustion heats. For comparison, acetylene is included in the list. Although oxyacetylene is the most common OFW fuel, each of the other gases can be used in certain applications—typically limited to welding of sheet metal and metals with low melting temperatures, and brazing (Section 30.1). In addition, some users prefer these alternative gases for safety reasons.

The fuel that competes most closely with acetylene in burning temperature and heating value is methylacetylene-propadiene. It is a fuel developed by the Dow Chemical Company sold under the trade name ***MAPP***. MAPP (C_3H_4) has heating characteristics similar to acetylene and can be stored under pressure as a liquid, thus avoiding the special storage problems associated with C_2H_2.

When hydrogen is burned with oxygen as the fuel, the process is called ***oxyhydrogen welding*** (OHW). As shown in Table 29.2, the welding temperature in OHW

TABLE • 29.2 Gases used in oxyfuel welding and/or cutting, with flame temperatures and heats of combustion.

Fuel	Temperature[a] °C	Temperature[a] °F	Heat of Combustion MJ/m3	Heat of Combustion Btu/ft^3
Acetylene (C_2H_2)	3087	5589	54.8	1470
MAPP[b] (C_3H_4)	2927	5301	91.7	2460
Hydrogen (H_2)	2660	4820	12.1	325
Propylene[c] (C_3H_6)	2900	5250	89.4	2400
Propane (C_3H_8)	2526	4579	93.1	2498
Natural gas[d]	2538	4600	37.3	1000

Compiled from [10].

[a]Neutral flame temperatures are compared because this is the flame that would most commonly be used for welding.

[b]MAPP is the commercial abbreviation for methylacetylene-propadiene.

[c]Propylene is used primarily in flame cutting.

[d]Data are based on methane gas (CH_4); natural gas consists of ethane (C_2H_6) as well as methane; flame temperature and heat of combustion vary with composition.

is below that possible in oxyacetylene welding. In addition, the color of the flame is not affected by differences in the mixture of hydrogen and oxygen, and therefore it is more difficult for the welder to adjust the torch.

Other fuels used in OFW include propane and natural gas. Propane (C_3H_8) is more closely associated with brazing, soldering, and cutting operations than with welding. Natural gas consists mostly of ethane (C_2H_6) and methane (CH_4). When mixed with oxygen it achieves a high temperature flame and is becoming more common in small welding shops.

Pressure Gas Welding This is a special OFW process, distinguished by type of application rather than fuel gas. ***Pressure gas welding*** (PGW) is a fusion-welding process in which coalescence is obtained over the entire contact surfaces of the two parts by heating them with an appropriate fuel mixture (usually oxyacetylene gas) and then applying pressure to bond the surfaces. A typical application is illustrated in Figure 29.23.

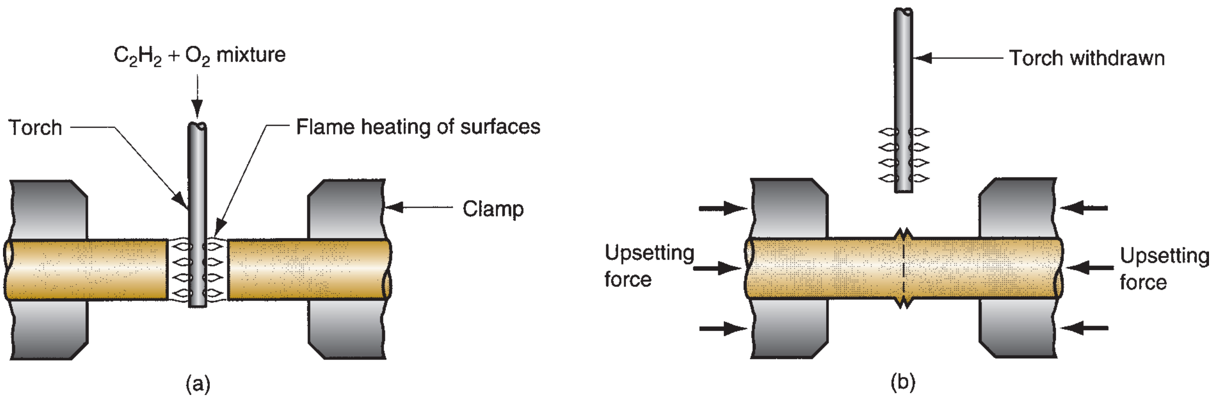

FIGURE 29.23 An application of pressure gas welding: (a) heating of the two parts, and (b) applying pressure to form the weld.

Parts are heated until melting begins on the surfaces. The heating torch is then withdrawn, and the parts are pressed together and held at high pressure while solidification occurs. No filler metal is used in PGW.

29.4 Other Fusion-Welding Processes

Some fusion-welding processes cannot be classified as arc, resistance, or oxyfuel welding. Each of these other processes uses a unique technology to develop heat for melting; and typically, the applications are unique.

Electron-Beam Welding Electron-beam welding (EBW) is a fusion-welding process in which the heat for welding is produced by a highly focused, high-intensity stream of electrons impinging against the work surface. The equipment is similar to that used for electron-beam machining (Section 25.3.2). The electron beam gun operates at high voltage to accelerate the electrons (e.g., 10–150 kV typical), and beam currents are low (measured in milliamps). The power in EBW is not exceptional, but power density is. High power density is achieved by focusing the electron beam on a very small area of the work surface, so that the power density PD is based on

$$PD = \frac{f_1 EI}{A} \tag{29.5}$$

where PD = power density, W/mm^2 (W/in^2, which can be converted to Btu/sec-in^2 by dividing by 1055.); f_1 = heat transfer factor (typical values for EBW range from 0.8 to 0.95 [9]); E = accelerating voltage, V; I = beam current, A; and A = the work surface area on which the electron beam is focused, mm^2 (in^2). Typical weld areas for EBW range from 13×10^{-3} to 2000×10^{-3} mm^2 (20×10^{-6}–3000×10^{-6} in^2).

The process had its beginnings in the 1950s in the atomic power field. When first developed, welding had to be carried out in a vacuum chamber to minimize the disruption of the electron beam by air molecules. This requirement was, and still is, a serious inconvenience in production, due to the time required to evacuate the chamber prior to welding. The pump-down time, as it is called, can take as long as an hour, depending on the size of the chamber and the level of vacuum required. Today, EBW technology has progressed to where some operations are performed without a vacuum. Three categories can be distinguished: (1) ***high-vacuum welding*** (EBW-HV), in which welding is carried out in the same vacuum as beam generation; (2) ***medium-vacuum welding*** (EBW-MV), in which the operation is performed in a separate chamber where only a partial vacuum is achieved; and (3) ***nonvacuum welding*** (EBW-NV), in which welding is accomplished at or near atmospheric pressure. The pump-down time during work part loading and unloading is reduced in medium-vacuum EBW and minimized in nonvacuum EBW, but there is a price paid for this advantage. In the latter two operations, the equipment must include one or more vacuum dividers (very small orifices that impede air flow but permit passage of the electron beam) to separate the beam generator (which requires a high vacuum) from the work chamber. Also, in nonvacuum EBW, the work must be located close to the orifice of the electron beam gun, approximately 13 mm (0.5 in) or less. Finally, the lower vacuum processes cannot achieve the high weld qualities and depth-to-width ratios accomplished by EBW-HV.

Any metals that can be arc welded can be welded by EBW, as well as certain refractory and difficult-to-weld metals that are not suited to AW. Work sizes range from thin foil to thick plate. EBW is applied mostly in the automotive, aerospace, and nuclear industries. In the automotive industry, EBW assembly includes aluminum manifolds, steel torque converters, catalytic converters, and transmission components. In these and other applications, electron-beam welding is noted for high-quality welds with deep and/or narrow profiles, limited heat affected zone, and low thermal distortion. Welding speeds are high compared to other continuous welding operations. No filler metal is used, and no flux or shielding gases are needed. Disadvantages of EBW include high equipment cost, need for precise joint preparation and alignment, and the limitations associated with performing the process in a vacuum, as previously discussed. In addition, there are safety concerns because EBW generates X-rays from which humans must be shielded.

Laser-Beam Welding Laser-beam welding (LBW) is a fusion-welding process in which coalescence is achieved by the energy of a highly concentrated, coherent light beam focused on the joint to be welded. The term ***laser*** is an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. This same technology is used for laser-beam machining (Section 25.3.3). LBW is normally performed with shielding gases (e.g., helium, argon, nitrogen, and carbon dioxide) to prevent oxidation. Filler metal is not usually added.

LBW produces welds of high quality, deep penetration, and narrow heat-affected zone. These features are similar to those achieved in electron-beam welding, and the two processes are often compared. There are several advantages of LBW over EBW: no vacuum chamber is required, no X-rays are emitted, and laser beams can be focused and directed by optical lenses and mirrors. On the other hand, LBW does not possess the capability for the deep welds and high depth-to-width ratios of EBW. Maximum depth in laser welding is about 19 mm (0.75 in), whereas EBW can be used for weld depths of 50 mm (2 in) or more; and the depth-to-width ratios in LBW are typically limited to around 5:1. Because of the highly concentrated energy in the small area of the laser beam, the process is often used to join small parts.

Electroslag Welding This process uses the same basic equipment as in some arc-welding operations, and it utilizes an arc to initiate welding. However, it is not an AW process because an arc is not used during welding. ***Electroslag welding*** (ESW) is a fusion-welding process in which coalescence is achieved by hot, electrically conductive molten slag acting on the base parts and filler metal. As shown in Figure 29.24,

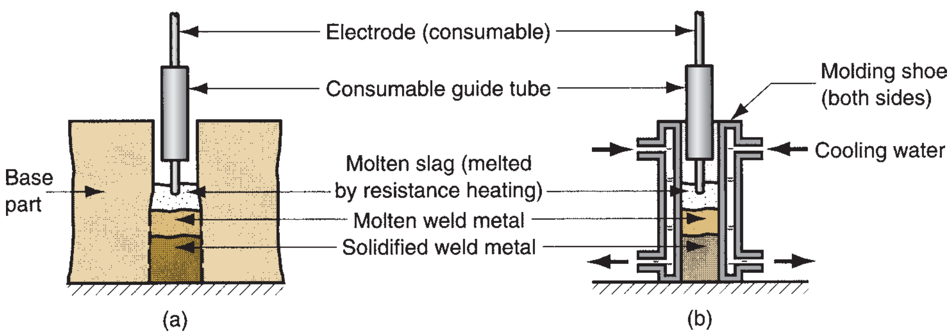

FIGURE 29.24 Electroslag welding (ESW): (a) front view with molding shoe removed for clarity; (b) side view showing schematic of molding shoe. Setup is similar to electrogas welding (Figure 29.7) except that resistance heating of molten slag is used to melt the base and filler metals.

the general configuration of ESW is similar to electrogas welding. It is performed in a vertical orientation (shown here for butt welding), using water-cooled molding shoes to contain the molten slag and weld metal. At the start of the process, granulated conductive flux is put into the cavity. The consumable electrode tip is positioned near the bottom of the cavity, and an arc is generated for a short while to start melting the flux. Once a pool of slag has been created, the arc is extinguished and the current passes from the electrode to the base metal through the conductive slag, so that its electrical resistance generates heat to maintain the welding process. Because the density of the slag is less than that of the molten metal, it remains on top to protect the weld pool. Solidification occurs from the bottom, while additional molten metal is supplied from above by the electrode and the edges of the base parts. The process gradually continues until it reaches the top of the joint.

Thermit Welding ***Thermit*** is a trademark name for ***thermite***, a mixture of aluminum powder and iron oxide that produces an exothermic reaction when ignited. It is used in incendiary bombs and for welding. As a welding process, the use of Thermit dates from around 1900. ***Thermit welding*** (TW) is a fusion-welding process in which the heat for coalescence is produced by superheated molten metal from the chemical reaction of Thermit. Filler metal is obtained from the liquid metal; and although the process is used for joining, it has more in common with casting than it does with welding.

Finely mixed powders of aluminum and iron oxide (in a 1:3 mixture), when ignited at a temperature of around 1300°C (2300°F), produce the following chemical reaction:

$$8Al + 3Fe_3O_4 \rightarrow 9Fe + 4Al_2O_3 + \text{heat} \tag{29.6}$$

The temperature from the reaction is around 2500°C (4500°F), resulting in superheated molten iron plus aluminum oxide that floats to the top as a slag and protects the iron from the atmosphere. In Thermit welding, the superheated iron (or steel if the mixture of powders is formulated accordingly) is contained in a crucible located above the joint to be welded, as indicated by the diagram of the TW process in Figure 29.25. After the reaction is complete (about 30 s, irrespective of the amount of Thermit involved), the crucible is tapped and the liquid metal flows into a mold built specially to surround the weld joint. Because the entering metal is so hot, it melts the edges of the base parts, causing coalescence upon solidification. After cooling, the mold is broken away, and the gates and risers are removed by oxyacetylene torch or other method.

Thermit welding has applications in joining of railroad rails (as pictured in the figure), and repair of cracks in large steel castings and forgings such as ingot molds,

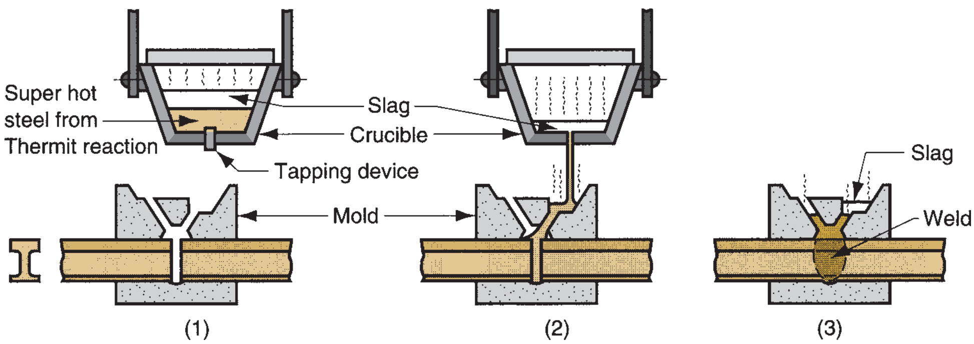

FIGURE 29.25 Thermit welding: (1) Thermit ignited; (2) crucible tapped, superheated metal flows into mold; (3) metal solidifies to produce weld joint.

large diameter shafts, frames for machinery, and ship rudders. The surface of the weld in these applications is often sufficiently smooth so that no subsequent finishing is required.

29.5 Solid-State Welding

In solid state-welding, coalescence of the part surfaces is achieved by (1) pressure alone, or (2) heat and pressure. For some solid-state processes, time is also a factor. If both heat and pressure are used, the amount of heat by itself is not sufficient to cause melting of the work surfaces. In other words, fusion of the parts would not occur using only the heat that is externally applied in these processes. In some cases, the combination of heat and pressure, or the particular manner in which pressure alone is applied, generates sufficient energy to cause localized melting of the faying surfaces. Filler metal is not added in solid-state welding.

29.5.1 GENERAL CONSIDERATIONS IN SOLID-STATE WELDING

In most of the solid-state processes, a metallurgical bond is created with little or no melting of the base metals. To metallurgically bond two similar or dissimilar metals, the two metals must be brought into intimate contact so that their cohesive atomic forces attract each other. In normal physical contact between two surfaces, such intimate contact is prohibited by the presence of chemical films, gases, oils, and so on. For atomic bonding to succeed, these films and other substances must be removed. In fusion welding (as well as other joining processes such as brazing and soldering), the films are dissolved or burned away by high temperatures, and atomic bonding is established by the melting and solidification of the metals in these processes. But in solid-state welding, the films and other contaminants must be removed by other means to allow metallurgical bonding to take place. In some cases, a thorough cleaning of the surfaces is done just before the welding process; while in other cases, the cleaning action is accomplished as an integral part of bringing the part surfaces together. To summarize, the essential ingredients for a successful solid-state weld are that the two surfaces must be very clean, and they must be brought into very close physical contact with each other to permit atomic bonding.

Welding processes that do not involve melting have several advantages over fusion-welding processes. If no melting occurs, then there is no heat-affected zone, and so the metal surrounding the joint retains its original properties. Many of these processes produce welded joints that comprise the entire contact interface between the two parts, rather than at distinct spots or seams, as in most fusion-welding operations. Also, some of these processes are quite applicable to bonding dissimilar metals, without concerns about relative thermal expansions, conductivities, and other problems that usually arise when dissimilar metals are melted and then solidified during joining.

29.5.2 SOLID STATE-WELDING PROCESSES

The solid-state welding group includes the oldest joining process as well as some of the most modern. Each process in this group has its own unique way of creating the bond at the faying surfaces. The coverage begins with forge welding, the first welding process.

Forge Welding Forge welding is of historic significance in the development of manufacturing technology. The process dates from about 1000 BCE, when blacksmiths of the ancient world learned to join two pieces of metal (Historical Note 29.1). ***Forge welding*** is a welding process in which the components to be joined are heated to hot working temperatures and then forged together by hammer or other means. Considerable skill was required by the craftsmen who practiced it to achieve a good weld by present-day standards. The process may be of historic interest; however, it is of minor commercial importance today except for its variants that are discussed below.

Cold Welding Cold welding (CW) is a solid-state welding process accomplished by applying high pressure between clean contacting surfaces at room temperature. The faying surfaces must be exceptionally clean for CW to work, and cleaning is usually done by degreasing and wire brushing immediately before joining. Also, at least one of the metals to be welded, and preferably both, must be very ductile and free of work hardening. Metals such as soft aluminum and copper can be readily cold welded. The applied compression forces in the process result in cold working of the metal parts, reducing thickness by as much as 50%; but they also cause localized plastic deformation at the contacting surfaces, resulting in coalescence. For small parts, the forces may be applied by simple hand-operated tools. For heavier work, powered presses are required to exert the necessary force. No heat is applied from external sources in CW, but the deformation process raises the temperature of the work somewhat. Applications of CW include making electrical connections.

Roll Welding Roll welding is a variation of either forge welding or cold welding, depending on whether external heating of the work parts is accomplished prior to the process. ***Roll welding*** (ROW) is a solid-state welding process in which pressure sufficient to cause coalescence is applied by means of rolls, either with or without external application of heat. The process is illustrated in Figure 29.26. If no external heat is supplied, the process is called ***cold-roll welding***; if heat is supplied, the term ***hot-roll welding*** is used. Applications of roll welding include cladding stainless steel to mild or low alloy steel for corrosion resistance, making bimetallic strips for measuring temperature, and producing "sandwich" coins for the U.S. mint.

Hot Pressure Welding Hot pressure welding (HPW) is another variation of forge welding in which coalescence occurs from the application of heat and pressure sufficient to cause considerable deformation of the base metals. The deformation disrupts the surface oxide film, thus leaving clean metal to establish a good bond between the two parts. Time must be allowed for diffusion to occur across the faying surfaces. The operation is usually carried out in a vacuum chamber or in the presence of a shielding medium. Principal applications of HPW are in the aerospace industry.

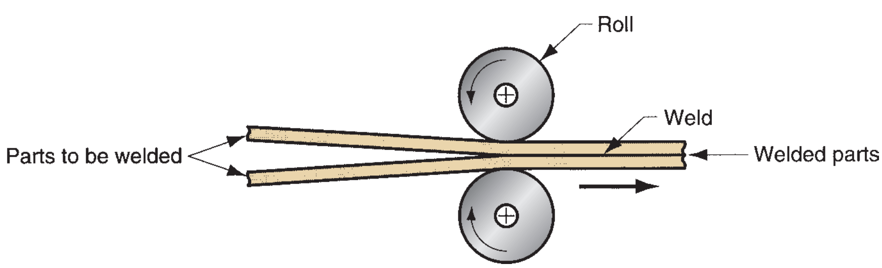

FIGURE 29.26
Roll welding (ROW).

Diffusion Welding Diffusion welding (DFW) is a solid-state welding process that results from the application of heat and pressure, usually in a controlled atmosphere, with sufficient time allowed for diffusion and coalescence to occur. Temperatures are well below the melting points of the metals (about 0.5 T_m is the maximum), and plastic deformation at the surfaces is minimal. The primary mechanism of coalescence is solid-state diffusion, which involves migration of atoms across the interface between contacting surfaces. Applications of DFW include the joining of high-strength and refractory metals in the aerospace and nuclear industries. The process is used to join both similar and dissimilar metals, and in the latter case a filler layer of a different metal is often sandwiched between the two base metals to promote diffusion. The time for diffusion to occur between the faying surfaces can be significant, requiring more than an hour in some applications [10].

Explosion Welding Explosion welding (EXW) is a solid-state welding process in which rapid coalescence of two metallic surfaces is caused by the energy of a detonated explosive. It is commonly used to bond two dissimilar metals, in particular to clad one metal on top of a base metal over large areas. Applications include production of corrosion-resistant sheet and plate stock for making processing equipment in the chemical and petroleum industries. The term ***explosion cladding*** is used in this context. No filler metal is used in EXW, and no external heat is applied. Also, no diffusion occurs during the process (the time is too short). The nature of the bond is metallurgical, in many cases combined with a mechanical interlocking that results from a rippled or wavy interface between the metals.

The process for cladding one metal plate on another can be described with reference to Figure 29.27. In this setup, the two plates are in a parallel configuration, separated by a certain gap distance, with the explosive charge above the upper plate, called the ***flyer plate***. A buffer layer (e.g., rubber, plastic) is often used between the explosive and the flyer plate to protect its surface. The lower plate, called the ***backer*** metal, rests on an anvil for support. When detonation is initiated, the explosive charge propagates from one end of the flyer plate to the other, caught in the stop-action view shown in Figure 29.27(2). One of the difficulties in comprehending what happens in EXW is the common misconception that an explosion occurs instantaneously; it is actually a progressive reaction, although admittedly very rapid—propagating at rates as high as 8500 m/s (28,000 ft/sec). The resulting high-pressure zone propels the flyer plate to collide with the backer metal progressively at high velocity, so that it takes on an angular shape as the explosion advances, as

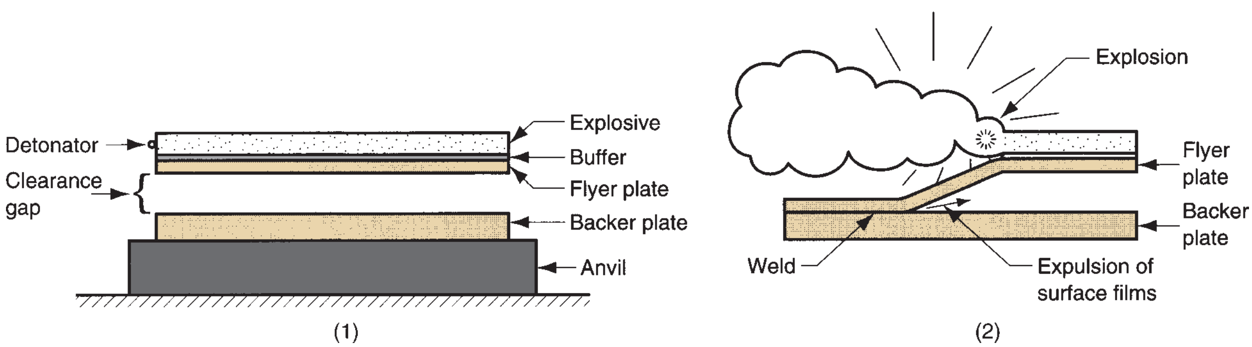

FIGURE 29.27 Explosive welding (EXW): (1) setup in the parallel configuration, and (2) during detonation of the explosive charge.

illustrated in the sketch. The upper plate remains in position in the region where the explosive has not yet detonated. The high-speed collision, occurring in a progressive and angular fashion as it does, causes the surfaces at the point of contact to become fluid, and any surface films are expelled forward from the apex of the angle. The colliding surfaces are thus chemically clean, and the fluid behavior of the metal, which involves some interfacial melting, provides intimate contact between the surfaces, leading to metallurgical bonding. Variations in collision velocity and impact angle during the process can result in a wavy or rippled interface between the two metals. This kind of interface strengthens the bond because it increases the contact area and tends to mechanically interlock the two surfaces.

Friction Welding Friction welding is a widely used commercial process, amenable to automated production methods. The process was developed in the (former) Soviet Union and introduced into the United States around 1960. ***Friction welding*** (FRW) is a solid-state welding process in which coalescence is achieved by frictional heat combined with pressure. The friction is induced by mechanical rubbing between the two surfaces, usually by rotation of one part relative to the other, to raise the temperature at the joint interface to the hot working range for the metals involved. Then the parts are driven toward each other with sufficient force to form a metallurgical bond. The sequence is portrayed in Figure 29.28 for welding two cylindrical parts, the typical application. The axial compression force upsets the parts, and a flash is produced by the material displaced. Any surface films that may have been on the contacting surfaces are expunged during the process. The flash must be subsequently trimmed (e.g., by turning) to provide a smooth surface in the weld region. When properly carried out, no melting occurs at the faying surfaces. No filler metal, flux, or shielding gases are normally used. Figure 29.29 shows the cross section of a friction welded joint.

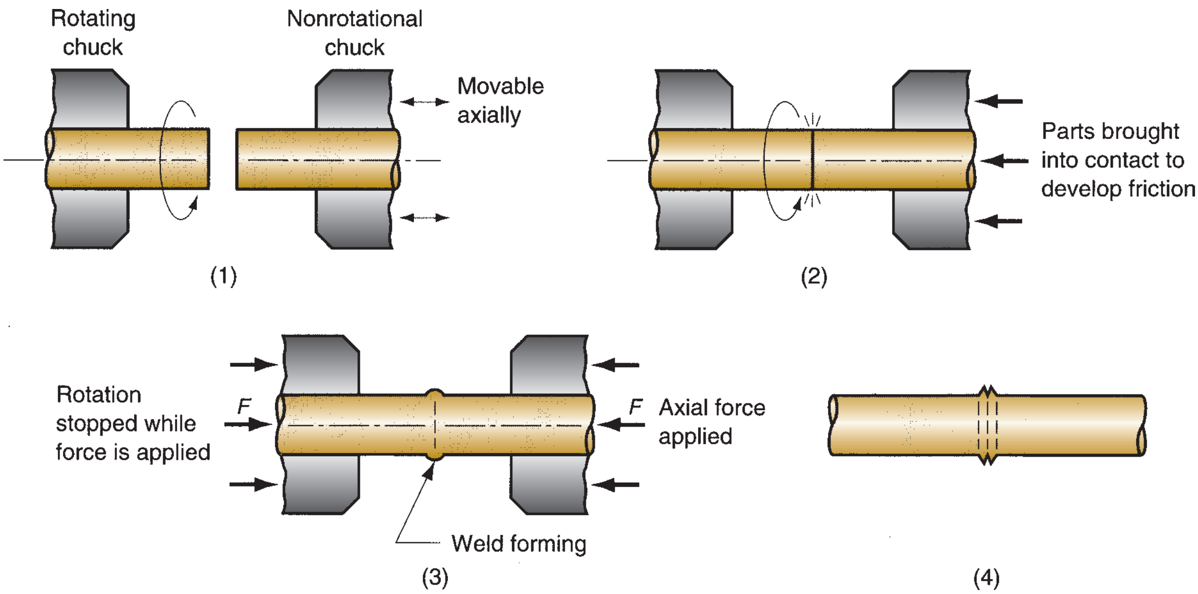

FIGURE 29.28 Friction welding (FRW): (1) rotating part, no contact; (2) parts brought into contact to generate friction heat; (3) rotation stopped and axial pressure applied; and (4) weld created.

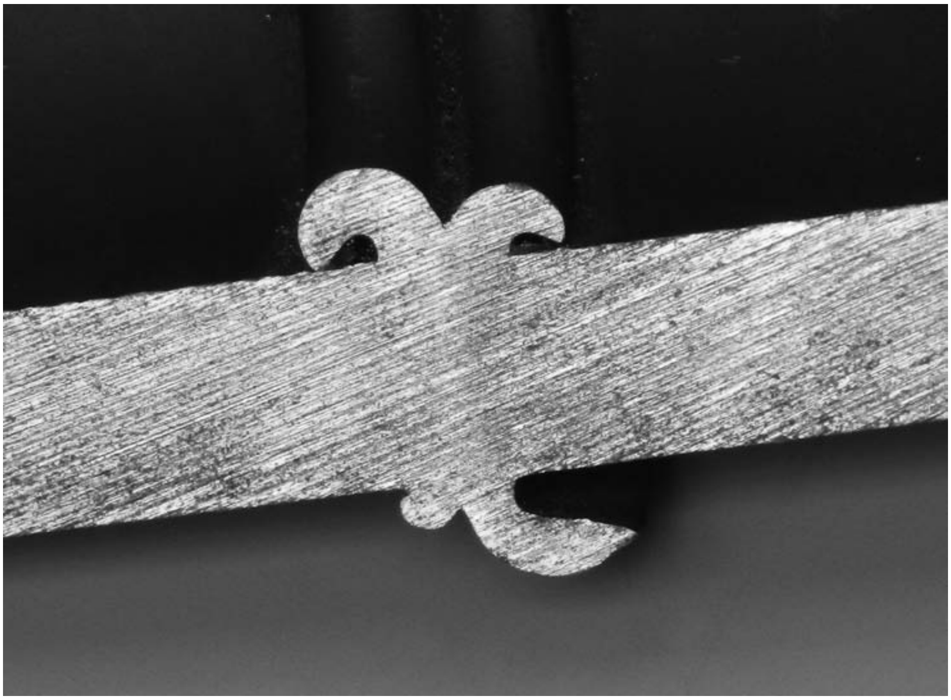

FIGURE 29.29 Cross section of a butt joint of two steel tubes welded by friction welding. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

Nearly all FRW operations use rotation to develop the frictional heat for welding. There are two principal drive systems, distinguishing two types of FRW: (1) continuous-drive friction welding, and (2) inertia friction welding. In ***continuous-drive friction welding***, one part is driven at a constant rotational speed and forced into contact with the stationary part at a certain force level so that friction heat is generated at the interface. When the proper hot working temperature has been reached, braking is applied to stop the rotation abruptly, and simultaneously the pieces are forced together at forging pressures. In ***inertia friction welding***, the rotating part is connected to a flywheel, which is brought up to a predetermined speed. Then the flywheel is disengaged from the drive motor, and the parts are forced together. The kinetic energy stored in the flywheel is dissipated in the form of friction heat to cause coalescence at the abutting surfaces. The total cycle for these operations is about 20 seconds.

Machines used for friction welding have the appearance of an engine lathe. They require a powered spindle to turn one part at high speed, and a means of applying an axial force between the rotating part and the nonrotating part. With its short cycle times, the process lends itself to mass production. It is applied in the welding of various shafts and tubular parts in industries such as automotive, aircraft, farm equipment, petroleum, and natural gas. The process yields a narrow heat affected zone and can be used to join dissimilar metals. However, at least one of the parts must be rotational, flash must usually be removed, and upsetting reduces the part lengths (which must be taken into consideration in product design).

The conventional friction welding operations discussed above utilize a rotary motion to develop the required friction between faying surfaces. A more recent version of the process is ***linear friction welding***, in which a linear reciprocating motion is

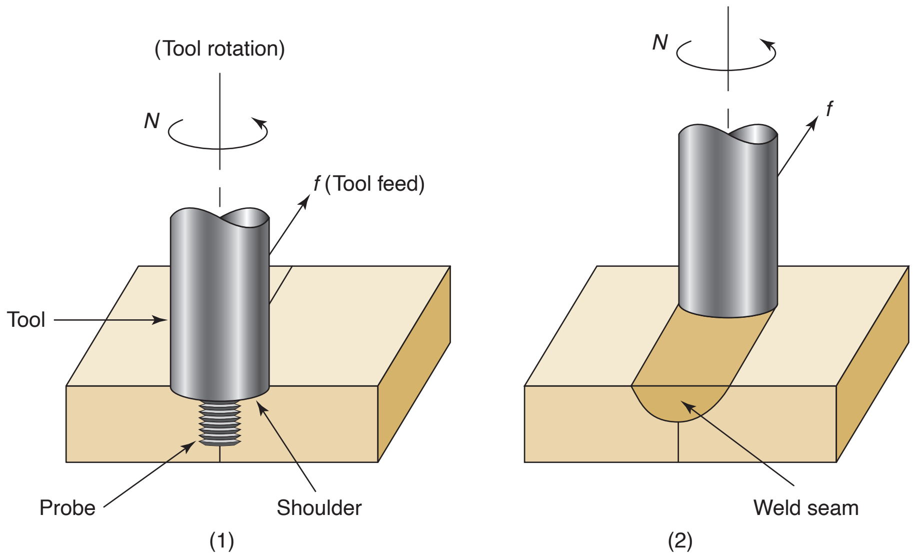

FIGURE 29.30 Friction stir welding (FSW): (1) rotating tool just prior to feeding into joint and (2) partially completed weld seam. N = tool rotation, f = tool feed.

used to generate friction heat between the parts. This eliminates the requirement for at least one of the parts to be rotational (e.g., cylindrical, tubular).

Friction Stir Welding Friction stir welding (FSW), illustrated in Figure 29.30, is a solid state welding process in which a rotating tool is fed along the joint line between two workpieces, generating friction heat and mechanically stirring the metal to form the weld seam. The process derives its name from this stirring or mixing action. FSW is distinguished from conventional FRW by the fact that friction heat is generated by a separate wear-resistant tool rather than by the parts themselves. FSW was developed in 1991 at The Welding Institute in Cambridge, UK.

The rotating tool is stepped, consisting of a cylindrical shoulder and a smaller probe projecting beneath it. During welding, the shoulder rubs against the top surfaces of the two parts, developing much of the friction heat, while the probe generates additional heat by mechanically mixing the metal along the butt surfaces. The probe has a geometry designed to facilitate the mixing action. The heat produced by the combination of friction and mixing does not melt the metal but softens it to a highly plastic condition. As the tool is fed forward along the joint, the leading surface of the rotating probe forces the metal around it and into its wake, developing forces that forge the metal into a weld seam. The shoulder serves to constrain the plasticized metal flowing around the probe.

The FSW process is used in the aerospace, automotive, railway, and shipbuilding industries. Typical applications are butt joints on large aluminum parts. Other metals, including steel, copper, and titanium, as well as polymers and composites have also been joined using FSW. Advantages in these applications include (1) good mechanical properties of the weld joint, (2) avoidance of toxic fumes, warping, shielding issues, and other problems associated with arc welding, (3) little distortion or shrinkage, and (4) good weld appearance. Disadvantages include (1) an exit hole is produced when the tool is withdrawn from the work, and (2) heavy-duty clamping of the parts is required.

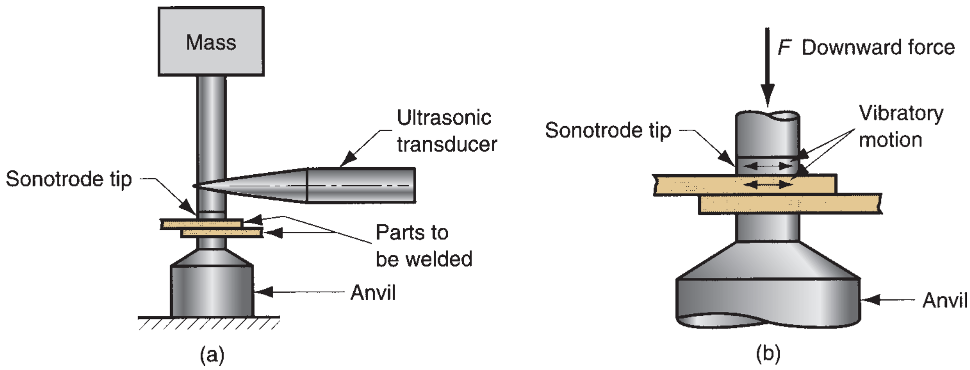

FIGURE 29.31 Ultrasonic welding (USW): (a) general setup for a lap joint; and (b) close-up of weld area.

Ultrasonic Welding Ultrasonic welding (USW) is a solid-state welding process in which two components are held together under modest clamping force, and oscillatory shear stresses of ultrasonic frequency are applied to the interface to cause coalescence. The operation is illustrated in Figure 29.31 for lap welding, the typical application. The oscillatory motion between the two parts breaks down any surface films to allow intimate contact and strong metallurgical bonding between the surfaces. Although heating of the contacting surfaces occurs due to interfacial rubbing and plastic deformation, the resulting temperatures are well below the melting point. No filler metals, fluxes, or shielding gases are required in USW.

The oscillatory motion is transmitted to the upper work part by means of a ***sonotrode***, which is coupled to an ultrasonic transducer. This device converts electrical power into high-frequency vibratory motion. Typical frequencies used in USW are 15 to 75 kHz, with amplitudes of 0.018 to 0.13 mm (0.0007–0.005 in). Clamping pressures are well below those used in cold welding and produce no significant plastic deformation between the surfaces. Welding times under these conditions are less than 1 sec.

USW operations are generally limited to lap joints on soft materials such as aluminum and copper. Welding harder materials causes rapid wear of the sonotrode contacting the upper work part. Work parts should be relatively small, and welding thicknesses less than 3 mm (1/8 in) is the typical case. Applications include wire terminations and splicing in electrical and electronics industries (eliminates the need for soldering), assembly of aluminum sheet-metal panels, welding of tubes to sheets in solar panels, and other tasks in small parts assembly.

29.6 Weld Quality

The purpose of any welding process is to join two or more components into a single structure. The physical integrity of the structure thus formed depends on the quality of the weld. The discussion of weld quality deals primarily with arc welding, the most widely used welding process and the one for which the quality issue is the most critical and complex.

Residual Stresses and Distortion The rapid heating and cooling in localized regions of the work during fusion welding, especially arc welding, result in thermal expansion and contraction that cause residual stresses in the weldment. These stresses, in turn, can cause distortion and warping of the welded assembly.

The situation in welding is complicated because (1) heating is very localized, (2) melting of the base metals occurs in these local regions, and (3) the location of heating and melting is in motion (at least in arc welding). Consider the butt welding of two plates by arc-welding shown in Figure 29.32(a). The operation begins at one end and travels to the opposite end. As it proceeds, a molten pool is formed from the base metal (and filler metal, if used) that quickly solidifies behind the moving arc. The portions of the work immediately adjacent to the weld bead become extremely hot and expand, while portions removed from the weld remain relatively cool. The weld pool quickly solidifies in the cavity between the two parts, and as it and the surrounding metal cool and contract, shrinkage occurs across the width of the weldment, as seen in Figure 29.32(b). The weld seam is left in residual tension, and reactionary compressive stresses are set up in regions of the parts away from the weld. Residual stresses and shrinkage also occurs along the length of the weld bead. Because the outer regions of the base parts have remained relatively cool and dimensionally unchanged, while the weld bead has solidified from very high temperatures and then contracted, residual tensile stresses remain longitudinally in the weld bead. These transverse and longitudinal stress patterns are depicted in Figure 29.32(c). The net result of these residual stresses, transversely and longitudinally, is likely to cause warping in the welded assembly as shown in Figure 29.32(d).

The arc-welded butt joint in the example is only one of a variety of joint types and welding operations. Thermally induced residual stresses and the accompanying distortion are a potential problem in nearly all fusion-welding processes and in certain solid-state welding operations in which significant heating takes place. Following are some techniques to minimize warping in a weldment: (1) ***Welding fixtures*** can be used to physically restrain movement of the parts during welding. (2) ***Heat sinks*** can be used to rapidly remove heat from sections of the welded parts to reduce distortion. (3) ***Tack welding*** at multiple points along the joint can create a rigid structure prior to

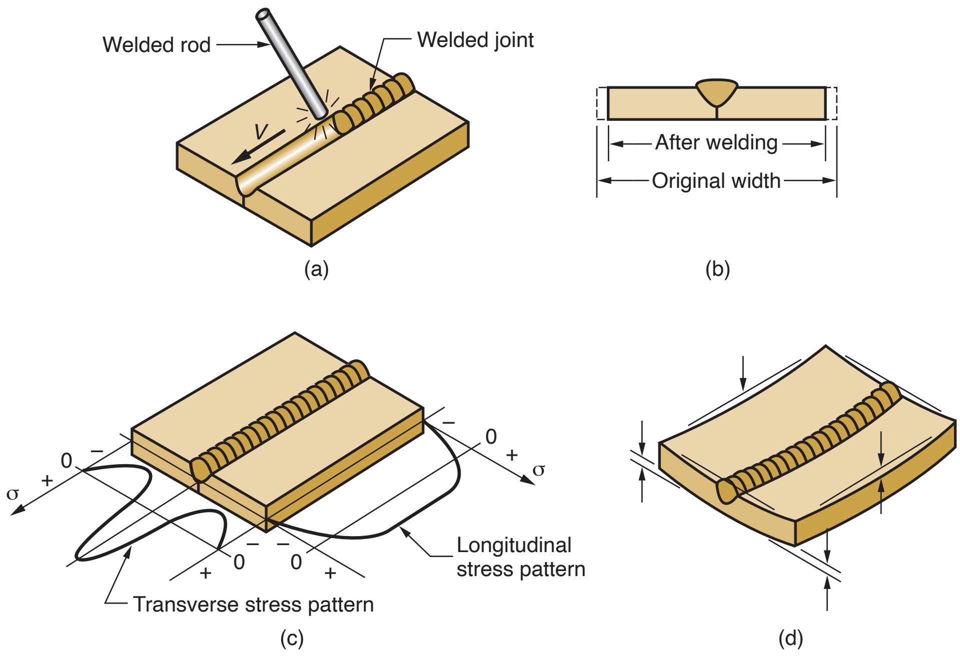

FIGURE 29.32 (a) Butt welding two plates; (b) shrinkage across the width of the welded assembly; (c) transverse and longitudinal residual stress pattern; and (d) likely warping in the welded assembly.

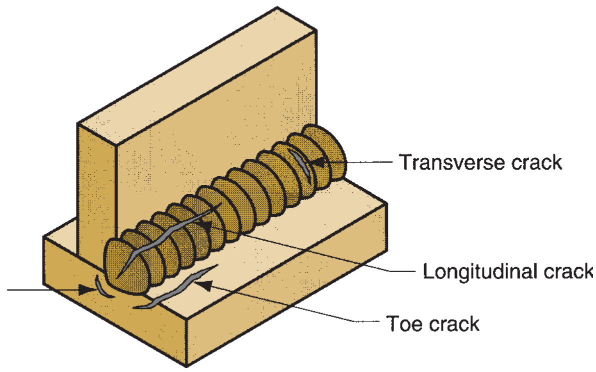

FIGURE 29.33 Various forms of welding cracks.

continuous seam welding. (4) ***Welding conditions*** (speed, amount of filler metal used, etc.) can be selected to reduce warping. (5) The base parts can be ***preheated*** to reduce the level of thermal stresses experienced by the parts. (6) ***Stress relief*** heat treatment can be performed on the welded assembly, either in a furnace for small weldments, or using methods that can be used in the field for large structures. (7) ***Proper design*** of the weldment itself can reduce the degree of warping.

Welding Defects In addition to residual stresses and distortion in the final assembly, other defects can occur in welding. Following is a brief description of each of the major categories, based on a classification in Cary [3]:

- ***Cracks***. Cracks are fracture-type interruptions either in the weld itself or in the base metal adjacent to the weld. This is perhaps the most serious welding defect because it constitutes a discontinuity in the metal that significant reduces weld strength. Several forms are defined in Figure 29.33. Welding cracks are caused by embrittlement or low ductility of the weld and/or base metal combined with high restraint during contraction. Generally, this defect must be repaired.
- ***Cavities***. These include various porosity and shrinkage voids. ***Porosity*** consists of small voids in the weld metal formed by gases entrapped during solidification. The shapes of the voids vary between spherical (blow holes) to elongated (worm holes). Porosity usually results from inclusion of atmospheric gases, sulfur in the weld metal, or contaminants on the surfaces. ***Shrinkage voids*** are cavities formed by shrinkage during solidification. Both of these cavity-type defects are similar to defects found in castings and emphasize the close kinship between casting and welding.
- ***Solid inclusions***. These are nonmetallic solid materials trapped inside the weld metal. The most common form is slag inclusions generated during arc-welding processes that use flux. Instead of floating to the top of the weld pool, globules of slag become encased during solidification of the metal. Another form of inclusion is metallic oxides that form during the welding of metals such as aluminum, which normally has a surface coating of Al_2O_3.
- ***Incomplete fusion***. Several forms of this defect are illustrated in Figure 29.34. Also known as ***lack of fusion***, it is simply a weld bead in which fusion has not occurred throughout the entire cross section of the joint. A related defect is ***lack of penetration*** which means that fusion has not penetrated deeply enough into the root of the joint.

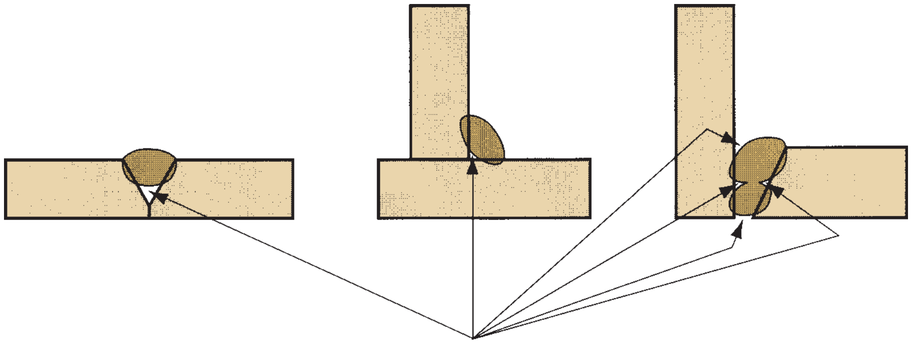

FIGURE 29.34 Several forms of incomplete fusion.

➢ ***Imperfect shape or unacceptable contour***. The weld should have a certain desired profile for maximum strength, as indicated in Figure 29.35(a) for a single V-groove weld. This weld profile maximizes the strength of the welded joint and avoids incomplete fusion and lack of penetration. Some of the common defects in weld shape and contour are illustrated in Figure 29.35.

➢ ***Miscellaneous defects***. This category includes ***arc strikes***, in which the welder accidentally allows the electrode to touch the base metal next to the joint, leaving a scar on the surface; and ***excessive spatter***, in which drops of molten weld metal splash onto the surface of the base parts.

Inspection and Testing Methods A variety of inspection and testing methods are available to check the quality of the welded joint. Standardized procedures have been developed and specified over the years by engineering and trade societies such as the American Welding Society (AWS). For purposes of discussion, these inspection and testing procedures can be divided into three categories: (1) visual, (2) nondestructive, and (3) destructive.

Visual inspection is no doubt the most widely used welding inspection method. An inspector visually examines the weldment for (1) conformance to dimensional specifications on the part drawing, (2) warping, and (3) cracks, cavities, incomplete fusion, and other visible defects. The welding inspector also determines if additional tests are warranted, usually in the nondestructive category. The limitation of visual inspection is that only surface defects are detectable; internal defects cannot be discovered by visual methods.

Nondestructive evaluation (NDE) includes various methods that do not damage the specimen being inspected. ***Dye-penetrant*** and ***fluorescent-penetrant tests*** are methods

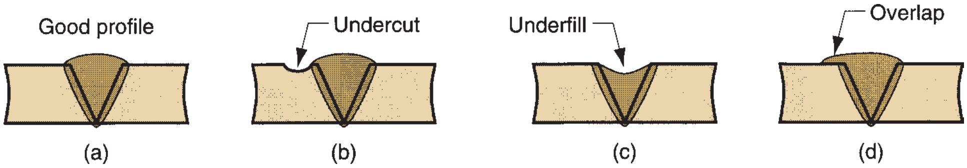

FIGURE 29.35 (a) Desired weld profile for single V-groove weld joint. Same joint but with several weld defects: (b) ***undercut***, in which a portion of the base metal part is melted away; (c) ***underfill***, a depression in the weld below the level of the adjacent base metal surface; and (d) ***overlap***, in which the weld metal spills beyond the joint onto the surface of the base part but no fusion occurs.

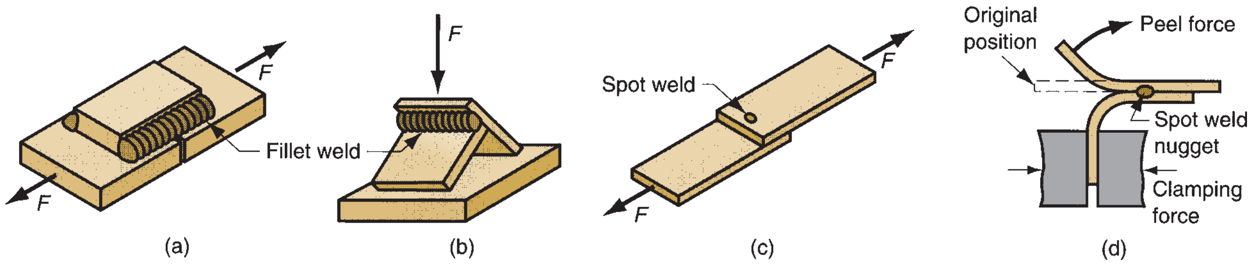

FIGURE 29.36 Mechanical tests used in welding: (a) tension–shear test of arc weldment, (b) fillet break test, (c) tension–shear test of spot weld, (d) peel test for spot weld.

for detecting small defects such as cracks and cavities that are open to the surface. Fluorescent penetrants are highly visible when exposed to ultraviolet light, and their use is therefore more sensitive than dyes.

Several other NDE methods should be mentioned. ***Magnetic particle testing*** is limited to ferromagnetic materials. A magnetic field is established in the subject part, and magnetic particles (e.g., iron filings) are sprinkled on the surface. Subsurface defects such as cracks and inclusions reveal themselves by distorting the magnetic field, causing the particles to be concentrated in certain regions on the surface. ***Ultrasonic testing*** involves the use of high-frequency sound waves ($>$ 20 kHz) directed through the specimen. Discontinuities (e.g., cracks, inclusions, porosity) are detected by losses in sound transmission. ***Radiographic testing*** uses X-rays or gamma radiation to detect flaws internal to the weld metal. It provides a photographic film record of any defects.

Destructive testing methods in which the weld is destroyed either during the test or to prepare the test specimen. They include mechanical and metallurgical tests. ***Mechanical tests*** are similar in purpose to conventional testing methods such as tensile tests and shear tests (Chapter 3). The difference is that the test specimen is a weld joint. Figure 29.36 presents a sampling of the mechanical tests used in welding. ***Metallurgical tests*** involve the preparation of metallurgical specimens of the weldment to examine such features as metallic structure, defects, extent and condition of heat-affected zone, presence of other elements, and similar phenomena.

29.7 Weldability

Weldability is the capacity of a metal or combination of metals to be welded into a suitably designed structure, and for the resulting weld joint(s) to possess the required metallurgical properties to perform satisfactorily in the intended service. Good weldability is characterized by the ease with which the welding process is accomplished, absence of weld defects, and acceptable strength, ductility, and toughness in the welded joint.

Factors that affect weldability include (1) welding process, (2) base metal properties, (3) filler metal, and (4) surface conditions. The welding process is significant. Some metals or metal combinations that can be readily welded by one process are difficult to weld by others. For example, stainless steel can be readily welded by most AW processes, but is considered a difficult metal for oxyfuel welding.

Properties of the base metal affect welding performance. Important properties include melting point, thermal conductivity, and coefficient of thermal expansion.

One might think that a lower melting point would mean easier welding. However, some metals melt too easily for good welding (e.g., aluminum). Metals with high thermal conductivity tend to transfer heat away from the weld zone, which can make them hard to weld (e.g., copper). High thermal expansion and contraction in the metal causes distortion problems in the welded assembly.

Dissimilar metals pose special problems in welding when their physical and/or mechanical properties are substantially different. Differences in melting temperature are an obvious problem. Differences in strength or coefficient of thermal expansion may result in high residual stresses that can lead to cracking. If a filler metal is used, it must be compatible with the base metal(s). In general, elements mixed in the liquid state that form a solid solution upon solidification will not cause a problem. Embrittlement in the weld joint may occur if the solubility limits are exceeded.

Surface conditions of the base metals can adversely affect the operation. For example, moisture can result in porosity in the fusion zone. Oxides and other solid films on the metal surfaces can prevent adequate contact and fusion from occurring.

29.8 Design Considerations in Welding

If an assembly is to be permanently welded, the designer should follow certain guidelines (compiled from [2], [3], and other sources):

- ***Design for welding***. The most basic guideline is that the product should be designed from the start as a welded assembly, and not as a casting or forging or other formed shape.
- ***Minimum parts***. Welded assemblies should consist of the fewest number of parts possible. For example, it is usually more cost efficient to perform simple bending operations on a part than to weld an assembly from flat plates and sheets.

The following guidelines apply to arc welding:

- ***Good fit-up of parts*** to be welded is important to maintain dimensional control and minimize distortion. Machining is sometimes required to achieve satisfactory fit-up.
- The assembly must provide access room to allow the welding gun to reach the welding area.
- Whenever possible, design of the assembly should allow ***flat welding*** to be performed, because this is the fastest and most convenient welding position. The possible welding positions are defined in Figure 29.37. The overhead position is the most difficult.

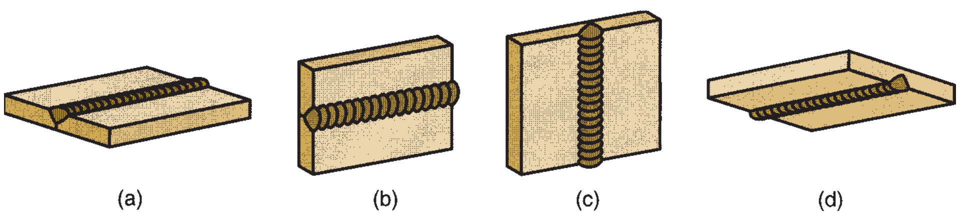

FIGURE 29.37 Welding positions (defined here for groove welds): (a) flat, (b) horizontal, (c) vertical, and (d) overhead.