CHAPTER

31 Solid-State Welding Processes

- This chapter describes an important family of joining processes in which the workpieces do not undergo a phase change and no filler metal is used; if heat is used, it is not externally applied, but instead is generated internally—for example, with friction.
- The chapter begins with a discussion of cold welding, followed by ultrasonic welding and the various forms of friction-welding processes.
- Resistance welding is then described, followed by explosion welding and diffusion bonding; these three processes have unique capabilities and applications suitable for a wide variety of materials and can be automated for large-scale production.
- The chapter also examines special capabilities of diffusion bonding combined with superplastic forming.
- Finally, economic considerations in welding are discussed.

31.1 Introduction

This chapter describes **solid-state welding** processes, in which joining takes place without fusion at the interface of the two parts to be welded. Unlike the situation with the fusion-welding processes described in Chapter 30, in solid-state welding no liquid or molten phase is present in the joint. The principle of solid-state welding is demonstrated best with the following example: If two clean surfaces are brought into close contact with each other under sufficient pressure, they form bonds and produce a joint. To form a strong bond, it is essential that the interface be free of oxide films, residues, metalworking fluids, other contaminants, and even adsorbed layers of gas.

Solid-state bonding involves one or more of the following phenomena:

- **Diffusion:** The transfer of atoms across an interface; thus, applying external heat improves the strength of the bond between the two surfaces being joined, as occurs in *diffusion bonding*. Heat may be generated internally by friction (as utilized in *friction welding*), through electrical-resistance heating (as in *resistance-welding* processes, such as *spot welding*), and externally by induction heating (as in *butt-welding* tubes).
- **Pressure:** The higher the pressure, the stronger is the interface (as in *roll bonding* and *explosion welding*), where plastic deformation also occurs. Pressure

and resistance heating may be combined, as in *flash welding, stud welding*, and *resistance projection welding*.

- **Relative interfacial movements:** When movements of the contacting surfaces (*faying surfaces*) occur (as in *ultrasonic welding*), even very small amplitudes will disturb the mating surfaces, break up any oxide films, and generate new, clean surfaces—thus improving the strength of the bond.

Most of the joining processes outlined here are now automated by *robotics, vision systems, sensors*, and *adaptive* and *computer controls* (see Part IX) for cost reduction, consistency, reliability of weld quality, and higher productivity. The costs involved in the joining process are outlined in Section 31.8.

31.2 Cold Welding and Roll Bonding

In *cold welding* (CW), pressure is applied to the workpieces through dies or rolls. Because of the *plastic deformation* involved, it is necessary that at least one (but preferably both) of the mating parts be ductile. Prior to welding, the interface is degreased, wire brushed, and wiped to remove oxide smudges. Cold welding can be used to join small workpieces made of soft, ductile metals. Applications include wire stock and electrical connections.

During the joining of two *dissimilar* metals that are mutually soluble, brittle *intermetallic compounds* may form (Section 4.2.2); these will produce a weak and brittle joint. An example occurs in the bonding of aluminum and steel, where a brittle intermetallic compound is formed at the interface. The best bond strength is obtained with two similar materials.

Roll Bonding. The pressure required for welding can be applied through a pair of rolls (Fig. 31.1); this process is called *roll bonding* or *roll welding* (ROW). Developed in the 1960s, roll bonding is used for manufacturing some U.S. coins (see Example 31.1). The process can be carried out at elevated temperatures (*hot roll bonding*). Surface preparation is important for interfacial strength.

Typical examples are the *cladding* of (a) pure aluminum over precipitation-hardened aluminum-alloy sheet (Alclad) and (b) stainless steel over mild steel (for corrosion resistance). A common application of roll bonding is the production of bimetallic strips for thermostats and similar controls using two layers of materials with different thermal-expansion coefficients. Bonding in only selected regions in the interface can be achieved by depositing a parting agent, such as graphite or ceramic, called *stop-off* (see Section 31.7).

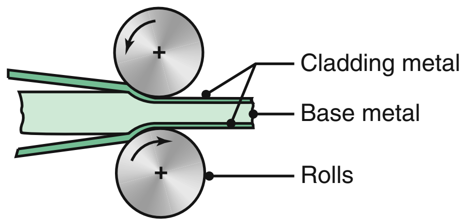

FIGURE 31.1 Schematic illustration of the roll bonding, or cladding, process.

EXAMPLE 31.1 Roll Bonding of the U.S. Quarter

The technique used for manufacturing composite U.S. quarters is the roll bonding of two outer layers of 75% Cu–25% Ni (cupronickel), where each layer is 1.2 mm (0.048 in.) thick, with an inner layer of pure copper 5.1 mm (0.20 in.) thick. To obtain good bond strength, the faying surfaces are cleaned chemically and wire brushed. First, the strips are rolled to a thickness of 2.29 mm (0.090 in.); a second rolling operation reduces the thickness to 1.36 mm (0.0535 in.). The strips thus undergo a total reduction in thickness of 82%.

Because volume constancy is maintained in plastic deformation, there is a major increase in the surface area between the layers, and it causes the generation of clean interfacial surfaces. This extension in surface area under the high pressure of the rolls, combined with the solid solubility of nickel in copper (see Section 4.2.1), produces a strong bond.

31.3 Ultrasonic Welding

In *ultrasonic welding* (USW), the faying surfaces of the two components are subjected to a static normal force and oscillating shearing (tangential) stresses. The shearing stresses are applied by the tip of a **transducer** (Fig. 31.2a), which is similar to that used for ultrasonic machining. (See Fig. 26.24a.) The frequency of oscillation is generally in the range from 10 to 75 kHz, although a lower or higher frequency can be employed. Proper coupling between the transducer and the tip (called—by analogy with *electrode*—a **sonotrode**, from the word *sonic*) is important for efficient operation.

The shearing stresses cause plastic deformation at the interface of the two components, breaking up oxide films and contaminants and thus allowing good contact and producing a strong solid-state bond. The temperature generated in the weld zone is usually in the range from one-third to one-half of the melting point (absolute scale) of the metals joined. Consequently, neither melting nor fusion takes place.

In certain situations, however, the temperature generated can be sufficiently high to cause metallurgical changes in the weld zone. Also, the mechanism responsible for the joining of *thermoplastics* by ultrasonic welding is different from that for metals, and melting does take place at the interface, because plastics have much lower melting temperatures. (See Table 7.2.)

The ultrasonic-welding process is versatile and reliable. It can be used with a wide variety of metallic and nonmetallic materials, including dissimilar metals (*bimetallic strips*). It is used extensively for the joining of plastics, for packaging with foils, and (in the automotive and consumer electronics industries) for the lap welding of sheet, foil, and thin wire. The welding tip can be replaced with *rotating disks* (Fig. 31.2b) for the seam welding of structures in which one component is sheet, foil, or polymer-woven material (a process similar *to resistance seam welding*, Section 31.5.2). Moderate skill is required to operate the equipment.

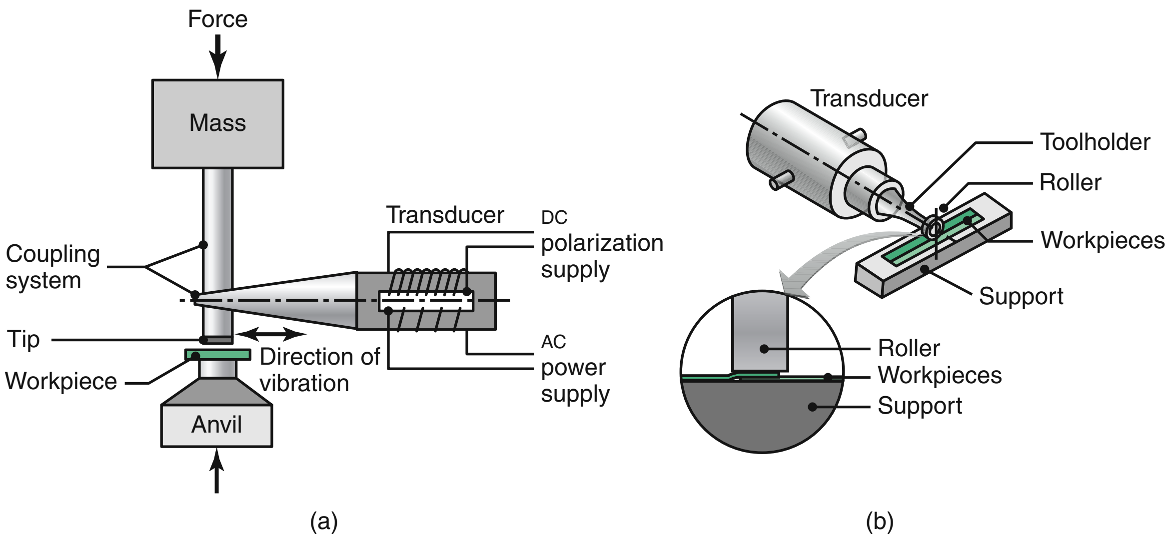

FIGURE 31.2 (a) Components of an ultrasonic-welding machine for making lap welds. The lateral vibrations of the tool tip cause plastic deformation and bonding at the interface of the workpieces. (b) Ultrasonic seam welding using a roller as the *sonotrode*.

31.4 Friction Welding

In the joining processes described thus far, the energy required for welding (typically chemical, electrical, or ultrasonic energy) is supplied from external sources. In *friction welding* (FRW), the heat required for welding is generated through (as the name implies) friction at the interface of the two components being joined. You can demonstrate the significant rise in temperature caused by friction by rubbing your hands together or by sliding down a rope rapidly.

In friction welding, developed in the 1940s, one of the workpiece components remains stationary while the other is placed in a chuck or collet and rotated at a high constant speed. The two members to be joined are then brought into contact under an axial force (Fig. 31.3). The surface speed of the rotating parts may be as high as 900 m/min (3,000 ft/min). After sufficient contact is established, the rotating member is brought to a quick stop (so that the weld is not destroyed by shearing) while the axial force is increased. Oxides and other contaminants at the interface are removed by the radially outward movement of the hot metal at the interface.

The rotating member must be clamped securely to the chuck or collet to resist both torque and axial forces without slipping. The pressure at the interface and the resulting friction produce sufficient heat for a strong joint to form.

The weld zone usually is confined to a narrow region; its size depends on the following parameters:

- Amount of heat generated
- Thermal conductivity of the materials
- Mechanical properties of the materials being joined at elevated temperatures.

The shape of the welded joint depends on the rotational speed and on the axial pressure applied (Fig. 31.4). These factors must be controlled to obtain a uniform,

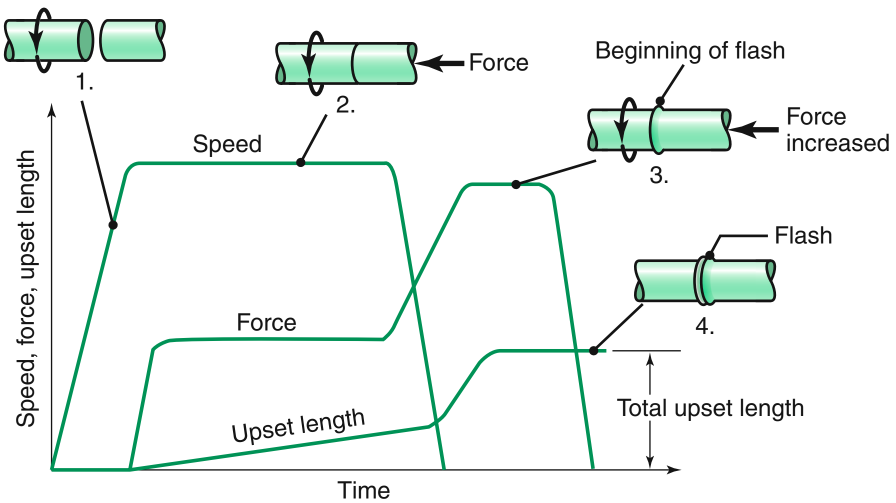

FIGURE 31.3 Sequence of operations in the friction-welding process: (1) The part on the left is rotated at high speed; (2) The part on the right is brought into contact with the part on the left under an axial force; (3) The axial force is increased, and the part on the left stops rotating; flash begins to form; (4) After a specified upset length or distance is achieved, the weld is completed. The *upset length* is the distance the two pieces move inward during welding after their initial contact; thus, the total length after welding is less than the sum of the lengths of the two pieces. The flash subsequently can be removed by machining or grinding.

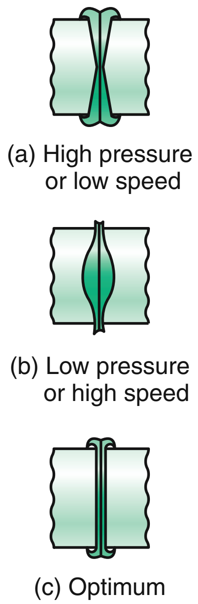

FIGURE 31.4 Shape of the fusion zones in friction welding as a function of the axial force applied and the rotational speed.

strong joint. The radially outward movement of the hot metal at the interface pushes oxides and other contaminants out of the interface.

Friction welding can be used to join a wide variety of materials, provided that one of the components has some rotational symmetry. Solid or tubular parts can be joined by this method with good joint strength. Solid steel bars up to 100 mm (4 in.) in diameter and pipes up to 250 mm (10 in.) in outside diameter have been friction welded successfully.

The surface speed of the rotating member may be as high as 15 m/s (3000 ft/min). Because of the combined heat and pressure, the interface in frictional welding develops a flash by plastic deformation (upsetting) of the heated zone. This flash (if objectionable) can easily be removed by machining or grinding. Friction-welding machines are fully automated, and the operator skill required is minimal—once individual cycle times for the complete operation are set properly.

Inertia Friction Welding. This process is a modification of friction welding, although the two terms have been used interchangeably. The energy required for frictional heating in inertia friction welding is supplied by the kinetic energy of a flywheel. The flywheel is accelerated to the proper speed, the two members are brought into contact, and an axial force is applied. As friction at the interface slows the flywheel, the axial force is increased. The weld is completed when the flywheel has come to a stop. The timing of this sequence is important for good weld quality.

The rotating mass in inertia-friction-welding machines can be adjusted for applications requiring different levels of energy (the levels depend on the workpiece size and properties). In one application of inertia friction welding, 10-mm- (0.4-in.-) diameter shafts are welded to automotive turbocharger impellers at a rate of one joint every 15 seconds.

Linear Friction Welding. In a further development of friction welding, the interface of the two components to be joined is subjected to a *linear* reciprocating motion, as opposed to a rotary motion. In *linear friction welding*, the components do not have to be circular or tubular in their cross section. The process is capable of welding square or rectangular components (as well as round parts) made of metals or plastics. In this process, one part is moved across the face of the other part by a balanced reciprocating mechanism.

In one application, a rectangular titanium-alloy part was friction welded at a linear frequency of 25 Hz with an amplitude of ± 2 mm (0.08 in.) under a pressure of 100 MPa (15,000 psi) acting on a 240 mm^2 (0.38 in^2) interface. Various other metal parts, with rectangular cross sections as large as 50 mm $\times$ 20 mm (2 in. $\times$ 0.8 in.), have been welded successfully.

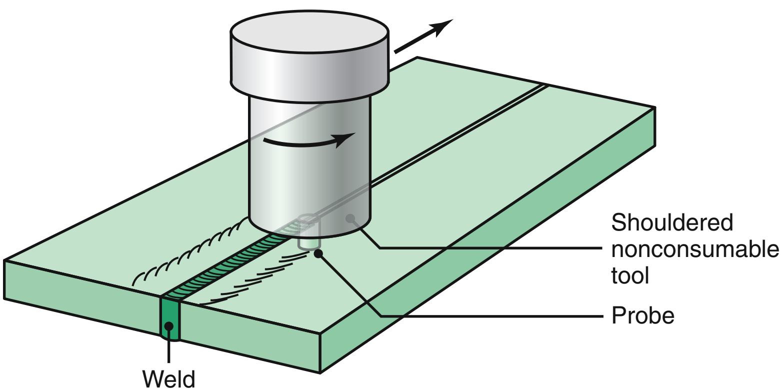

FIGURE 31.5 The principle of the friction-stir-welding process. Aluminum-alloy plates up to 75 mm (3 in.) thick have been welded by this process.

Friction Stir Welding. In conventional friction welding, heating of an interface is achieved through friction by rubbing two contacting surfaces. In the *friction-stir-welding* (FSW) process, developed in 1991, a third body is rubbed against the two surfaces to be joined. A rotating non-consumable probe, typically 5 to 6 mm in diameter and 5 mm high, is plunged into the joint (Fig. 31.5). The contact pressure causes frictional heating, raising the temperature to between 230° and

260°C (450° and 500°F). The probe at the tip of the rotating tool forces mixing (or stirring) of the material in the joint.

Materials such as aluminum, copper, steel, and titanium have been welded successfully, and developments are taking place to extend FSW applications to polymers and composite materials. The process is now being applied to aerospace, automotive, shipbuilding, and military vehicles, using sheet or plates. With developments in rotating-tool design, other possible applications include inducing microstructural changes, refining grain in materials, and improving localized toughness in castings.

The welding equipment can be a conventional, vertical-spindle milling machine (Fig. 24.15b), and the process is relatively easy to implement. The thickness of the welded material can be as little as 1 mm and as much as 50 mm (2 in.) welded in a single pass. Welds produced by friction stir welding have high quality, minimal pores, and a uniform material structure. The welds are produced with low heat input and therefore low distortion and little microstructural changes. No shielding gas or surface cleaning is required.

31.5 Resistance Welding

The category of *resistance welding* (RW) covers a number of processes in which the heat required for welding is produced by means of *electrical resistance* across the two components to be joined. These processes have major advantages, such as not requiring consumable electrodes, shielding gases, or flux.

The heat generated in resistance welding is given by the general expression

$$H = I^2Rt, \tag{31.1}$$

where

H = Heat generated in joules (watt-seconds)
I = Current (in amperes)
R = Resistance (in ohms)
t = Time of current flow (in seconds).

Equation (31.1) is often modified so that it represents the actual heat energy available in the weld by including a factor K, which denotes the energy losses through conduction and radiation. The equation then becomes

$$H = I^2RtK, \tag{31.2}$$

where the value of K is less than unity.

The *total resistance* is the sum of the following properties (see Fig. 31.6):

a. Resistances of the electrodes;
b. Electrode–workpiece contact resistance;
c. Resistances of the individual parts to be welded;
d. Contact resistance between the two workpieces to be joined (*faying surfaces*).

The actual temperature rise at the joint depends on the specific heat and the thermal conductivity of the metals to be joined. For example, metals such as aluminum and copper have high thermal conductivity, so they require high heat concentrations. Similar or dissimilar metals can be joined by resistance welding. The magnitude of the current in resistance-welding operations may be as high as 100,000 A, but the voltage is typically only 0.5 to 10 V.

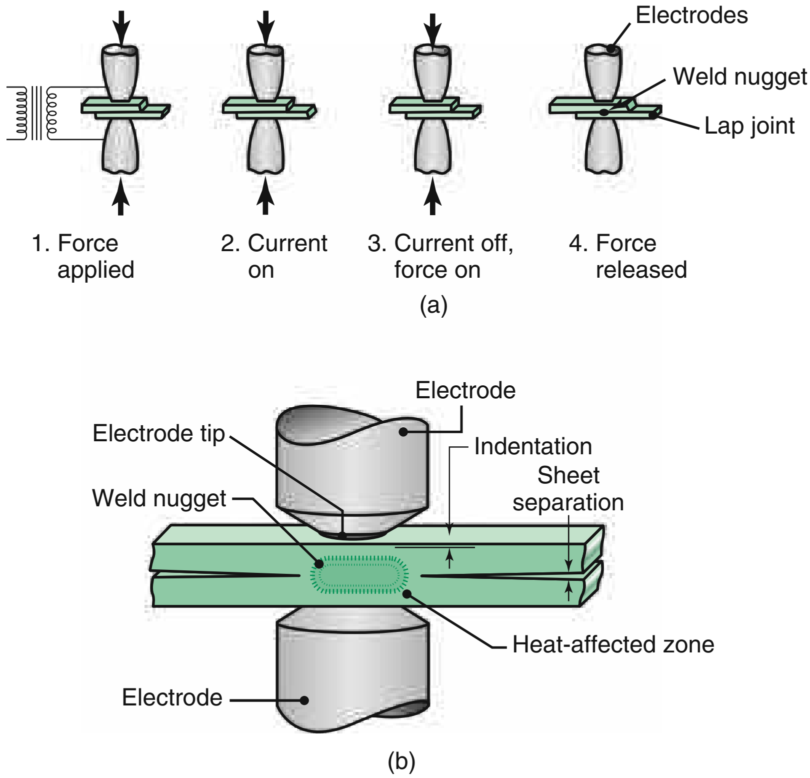

FIGURE 31.6 (a) Sequence of events in resistance spot welding. (b) Cross section of a spot weld, showing the weld nugget and the indentation of the electrode on the sheet surfaces. This is one of the most commonly used processes in sheet-metal fabrication and in automotive-body assembly.

The strength of the bond depends on surface roughness and on the cleanliness of the mating surfaces. Oil films, paint, and thick oxide layers should therefore be removed before welding. The presence of uniform, thin layers of oxide and of other contaminants is not as critical.

Developed in the early 1900s, resistance-welding processes require specialized machinery. Much of it is now operated by programmable computer control. Generally, the machinery is not portable, and the process is suitable primarily for use in manufacturing plants and machine shops. The operator skill required is minimal, particularly with modern machinery.

31.5.1 Resistance Spot Welding

In *resistance spot welding* (RSW), the tips of two opposing solid, cylindrical electrodes touch a lap joint of two sheet metals, and resistance heating produces a spot weld (Fig. 31.6a). In order to obtain a strong bond in the **weld nugget**, pressure is applied until the current is turned off and the weld has solidified. Accurate control and timing of the alternating electric current and of the pressure are essential in resistance welding. In the automotive industry, for example, the number of cycles ranges up to about 30 at a frequency of 60 Hz. (See also *high-frequency resistance welding* in Section 31.5.3.)

The weld nugget (Fig. 31.6b) is generally 6 to 10 mm (0.25 to 0375 in.) in diameter. The surface of the spot weld has a slightly discolored indentation. Currents range from 3000 to 40,000 A. The current level depends on the materials being welded and on their thicknesses. For example, the current is typically 10,000 A for steels and 13,000 A for aluminum. Electrodes generally are made of copper alloys and must have sufficient electrical conductivity and hot strength to maintain their shape.

Spot welding is the simplest and most commonly used resistance-welding process. Welding may be performed by means of single (most common) or multiple pairs of electrodes (as many as a hundred or more), and the required pressure is supplied through mechanical or pneumatic means. **Rocker-arm-type** spot-welding machines normally are used for smaller parts; **press-type** machines are used for larger workpieces. The shape and surface condition of the electrode tip and the accessibility of the site are important factors in spot welding. A variety of electrode shapes are used to spot-weld areas that are difficult to reach (Fig. 31.7).

Spot welding is used widely for fabricating sheet-metal parts. Examples range from attaching handles to stainless-steel cookware (Fig. 31.8a) to spot-welding mufflers (Fig. 31.8b) and large sheet-metal structures. Modern spot-welding equipment is computer controlled for optimum timing of current and pressure; its spot-welding guns are manipulated by programmable robots (Fig. 31.8c). Automobile bodies can have as many as 10,000 spot welds; they are welded at high rates with the use of multiple electrodes (see Fig. I.10 in the General Introduction).

Testing Spot Welds. Spot-welded joints may be tested for weld-nugget strength by means of the following techniques (Fig. 31.9):

- Tension-shear
- Cross-tension
- Twist
- Peel.

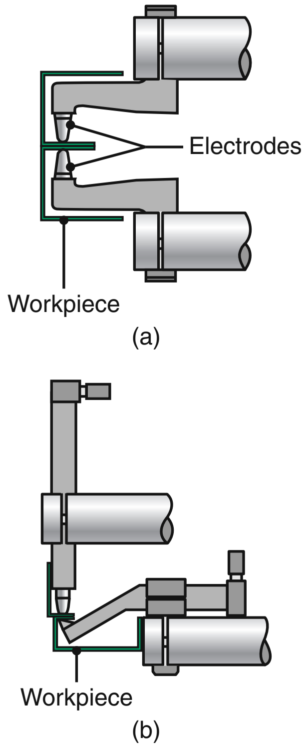

FIGURE 31.7 Two electrode designs for easy access to the components to be welded.

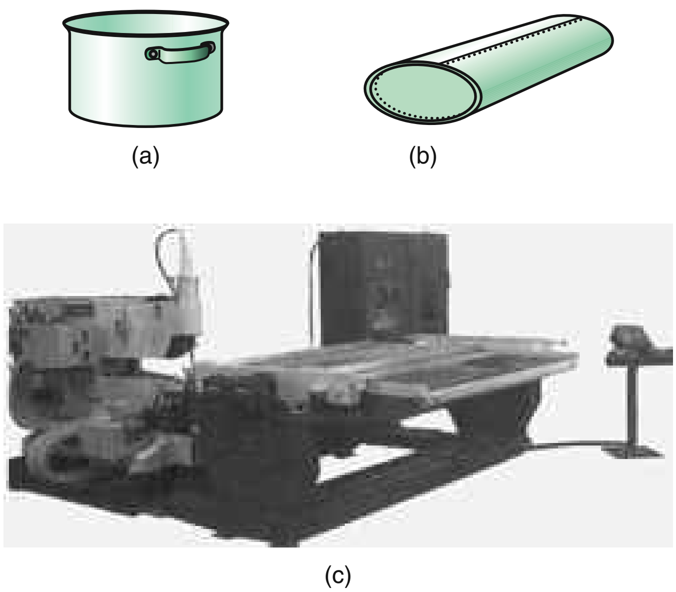

FIGURE 31.8 Spot-welded (a) cookware and (b) muffler. (c) An automated spot-welding machine. The welding tip can move in three principal directions. Sheets as large as 2.2 × 0.55 m (88 × 22 in.) can be accommodated in this machine with proper workpiece supports. *Source*: Courtesy of Taylor–Winfield Corporation.

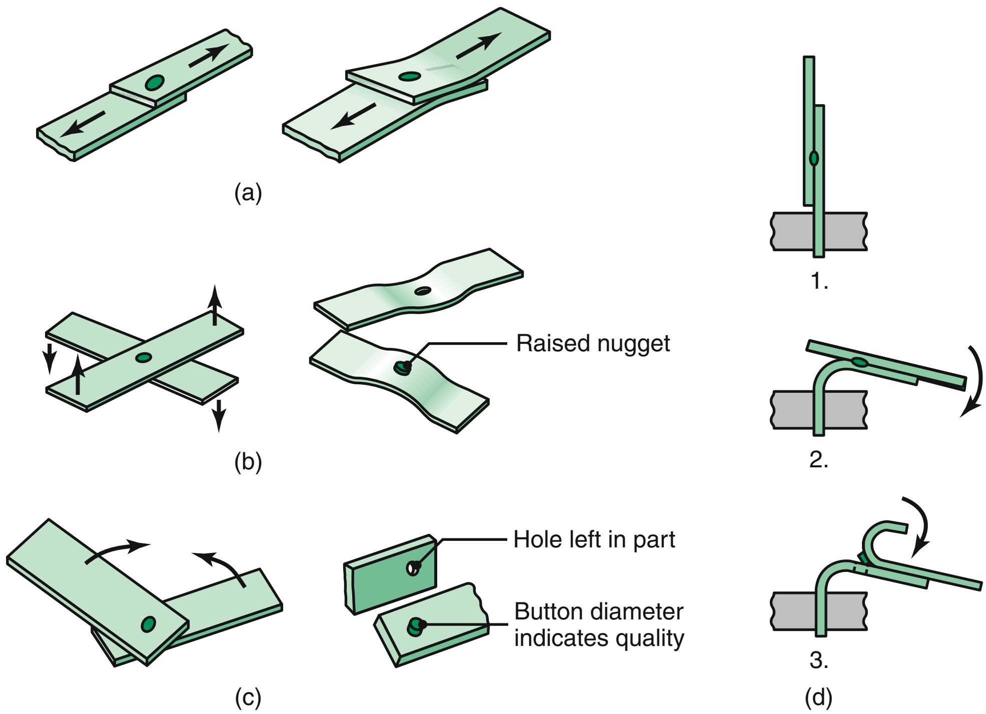

FIGURE 31.9 Test methods for spot welds: (a) tension-shear test, (b) cross-tension test, (c) twist test, (d) peel test (see also Fig. 32.9).

Because they are easy to perform and are inexpensive, tension-shear tests are commonly used in fabricating facilities. The cross-tension and twist tests are capable of revealing flaws, cracks, and porosity in the weld area. The peel test is commonly used for thin sheets. After the joint has been bent and peeled, the shape and size of the torn-out weld nugget are evaluated.

EXAMPLE 31.2 Heat Generated in Spot Welding

Assume that two 1-mm (0.04-in.) thick steel sheets are being spot-welded at a current of 5000 A and over a current flow time of 0.1 second by means of electrodes 5 mm (0.2 in.) in diameter. Estimate the heat generated and its distribution in the weld zone if the effective resistance in the operation is 200 $\mu\Omega$.

Solution According to Eq. (31.1),

$$\text{Heat} = (5000)^2(0.0002)(0.1) = 500 \text{ J}.$$

From the information given, the weld-nugget volume can be estimated to be 30 mm^3 (0.0018 in^3). Assume that the density for steel (Table 3.1) is 8000 kg/m^3 (0.008 g/mm^3). Then the weld nugget has a mass of 0.24 g. The heat required to melt 1 g of steel is about 1400 J, so the heat required to melt the weld nugget is (1400)(1400)(0.24) = 336 J. The remaining heat (164 J) is dissipated into the metal surrounding the nugget.

31.5.2 Resistance Seam Welding

Resistance seam welding (RSEW) is a modification of spot welding wherein the electrodes are replaced by rotating wheels or rollers (Fig. 31.10a). Using a continuous AC power supply, the electrically conducting rollers produce a spot weld whenever

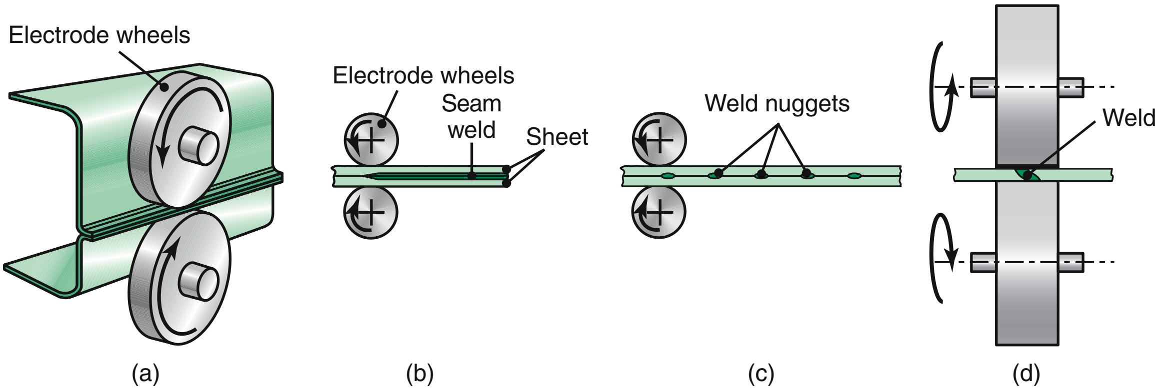

FIGURE 31.10 (a) Seam-welding process in which rotating rolls act as electrodes. (b) Overlapping spots in a seam weld. (c) Roll spot welds and (d) Mash seam welding.

the current reaches a sufficiently high level in the AC cycle. With a high enough frequency or slow enough traverse speed, these spot welds actually overlap into a continuous seam and produce a joint that is liquid tight and gastight (Fig. 31.10b).

In **roll spot welding**, current to the rollers is applied only intermittently, resulting in a series of spot welds at specified intervals along the length of the seam (Fig. 31.10c). In **mash seam welding** (Fig. 31.10d), the overlapping welds are about one to two times the sheet thickness, and the welded seam thickness is only about 90% of the original sheet thickness. This process is also used in producing *tailor-welded* sheet-metal blanks, which can be made by laser welding as well (see Section 16.2.2).

The RSEW process is used to make the longitudinal (side) seam of cans (for household products) mufflers, gasoline tanks, and other containers. The typical welding speed is 1.5 m/min (60 in./min) for thin sheets.

31.5.3 High-frequency Resistance Welding

High-frequency resistance welding (HFRW) is similar to seam welding, except that high-frequency current (up to 450 kHz) is employed. A typical application is the production of *butt-welded* tubing or pipe where the current is conducted through two sliding contacts (Fig. 31.11a) to the edges of roll-formed tubes. The heated edges then are pressed together by passing the tube through a pair of squeeze rolls. Any flash formed is then trimmed off.

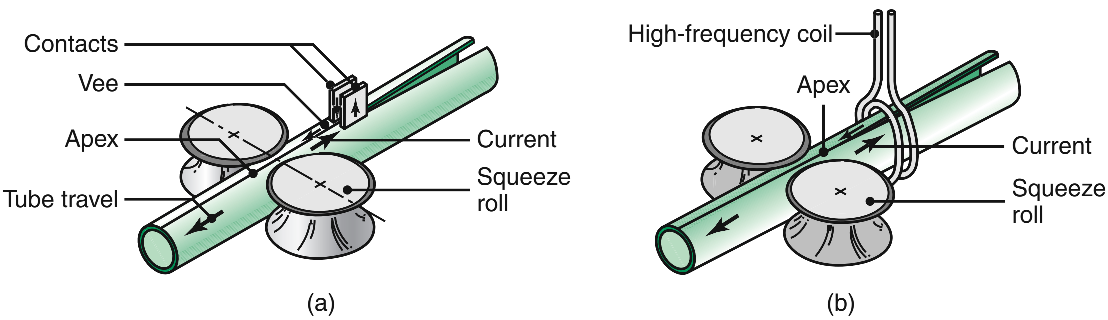

FIGURE 31.11 Two methods of high-frequency continuous butt welding of tubes.

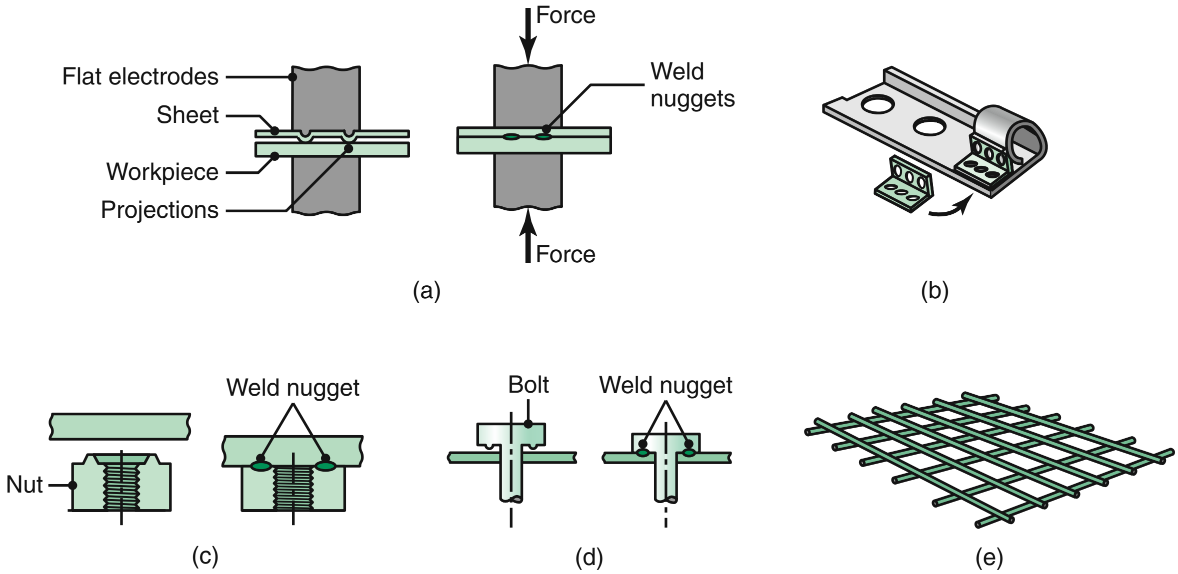

FIGURE 31.12 (a) Schematic illustration of resistance projection welding. (b) A welded bracket. (c) and (d) Projection welding of nuts or threaded bosses and studs. (e) Resistance-projection-welded grills.

Structural sections (such as I-beams) can be fabricated by HFRW by welding the webs and flanges made from long, flat pieces. Spiral pipe and tubing, finned tubes for heat exchangers, and wheel rims also may be made by this technique. In another method, called **high-frequency induction welding** (HFIW), the roll-formed tube is subjected to high-frequency induction heating, as shown in Fig. 31.11b.

31.5.4 Resistance Projection Welding

In *resistance projection welding* (RPW), high electrical resistance at the joint is developed by embossing one or more projections (*dimples*; see Fig. 16.36) on one of the surfaces to be welded (Fig. 31.12). The projections may be round or oval for design or strength purposes. High localized temperatures are generated at the projections, which are in contact with the flat mating part. The electrodes (typically made of copper-based alloys) are large and flat, and water cooled to keep their temperature low. Weld nuggets similar to those in spot welding are formed as the electrodes exert pressure to soften and compress the projections.

Spot-welding equipment can be used for resistance projection welding by modifying the electrodes. Although the embossing of the workpieces adds expense, the process produces a number of welds in one pass, extends electrode life, and is capable of welding metals of different thicknesses, such as a sheet welded over a plate. Nuts and bolts can be welded to sheets and plates by this process (Fig. 31.12c and d), with projections that are produced by machining or forging. Joining a network of rods and wires (such as the ones making up metal baskets, grills (Fig. 31.12e) oven racks, and shopping carts) also is considered resistance projection welding, because of the many small contact areas between crossing wires (grids).

31.5.5 Flash Welding

In *flash welding* (FW), also called **flash butt welding**, heat is generated very rapidly from the arc as the ends of the two members begin to make contact and develop an electrical resistance at the joint (Fig. 31.13a). After the proper temperature is

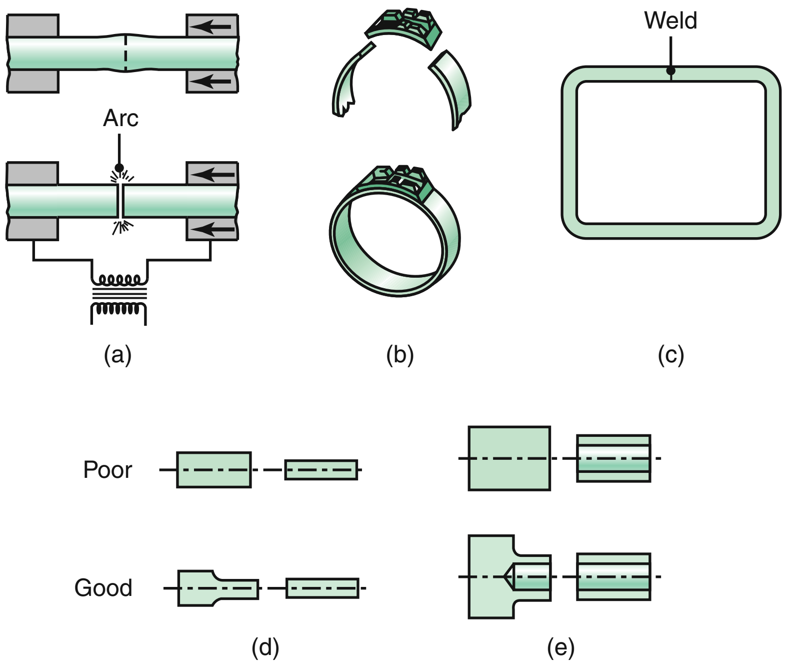

FIGURE 31.13 (a) Flash-welding process for end-to-end welding of solid rods or tubular parts. (b) and (c) Typical parts made by flash welding. (d) and (e) Some design guidelines for flash welding.

reached and the interface begins to soften, an axial force is applied at a controlled rate and a weld is formed by plastic deformation of the joint. The mechanism is called *hot upsetting*, and the term *upset welding* (UW) also is used for this process. Some molten metal is expelled from the joint as a shower of sparks during the process—hence the name *flash welding*. Because of the presence of an arc, the process can also be classified as arc welding.

Impurities and contaminants are squeezed out during this operation; therefore, the quality of the weld is good. However, a significant amount of material may be burned off during the welding process. The joint may be machined later to improve its appearance. The machines for flash welding usually are automated and large and have a variety of power supplies ranging from 10 to 1500 kVA.

The flash-welding process is suitable for end-to-end or edge-to-edge joining of sheets of similar or dissimilar metals 0.2 to 25 mm (0.01 to 1 in.) thick and for end-joining bars 1 to 75 mm (0.05 to 3 in.) in diameter. Thinner sections have a tendency to buckle under the axial force applied during welding. Rings made by forming processes (such as those shown in Fig. 16.22) also can be flash butt welded. In addition, the process is used to repair broken band-saw blades with the use of fixtures that are mounted on the band-saw frame.

The flash-welding process can be automated for reproducible welding operations. Typical applications are the joining of pipe and of tubular shapes for metal furniture and windows. The process is also used for welding the ends of sheets or coils of wire in continuously operating rolling mills (Chapter 13) and in the feeding of wire-drawing equipment (Chapter 15). Once the appropriate process parameters are established, the required operator skill is minimal. Some design guidelines for mating surfaces in flash welding are shown in Fig. 31.13d and e. Note the importance of uniform cross sections at the joint.

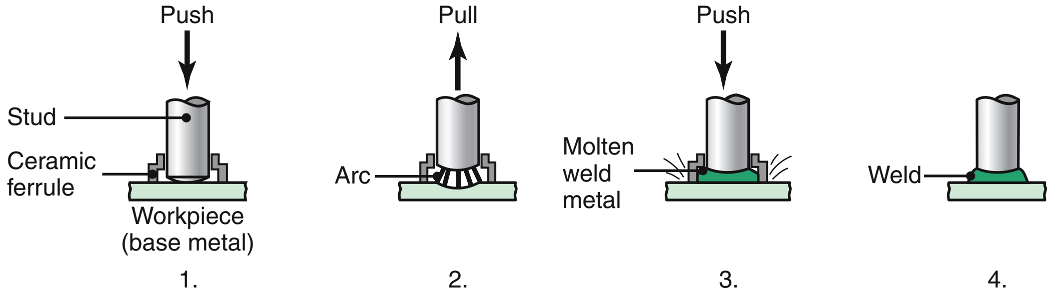

FIGURE 31.14 The sequence of operations in stud welding commonly used for welding bars, threaded rods, and various fasteners onto metal plates.

31.5.6 Stud Welding

Stud welding (SW) is also called *stud arc welding* and is similar to flash welding. The stud (which may be a small part or, more commonly, a threaded rod, hanger, or handle) serves as one of the electrodes while being joined to another component, which is usually a flat plate (Fig. 31.14). Polarity for aluminum is usually direct-current electrode positive (DCEP), and for steel it is direct-current electrode negative (DCEN).

In order to concentrate the heat generated, prevent oxidation, and retain the molten metal in the weld zone, a disposable ceramic ring (*ferrule*) is placed around the joint. The equipment for stud welding can be automated with various controls for arcing and for applying pressure. Portable stud-welding equipment also is available. Typical applications of stud welding include automobile bodies, electrical panels, and shipbuilding; the process is also used in building construction.

In **capacitor-discharge stud welding**, a DC arc is produced from a capacitor bank. No ferrule or flux is required, because the welding time is very short—on the order of 1 to 6 milliseconds. The choice between this process and stud arc welding depends on such factors as the types of metals to be joined, the workpiece thickness and cross section, the stud diameter, and the shape of the joint.

31.5.7 Percussion Welding

The resistance-welding processes already described usually employ an electrical transformer to meet the power requirements. Alternatively, the electrical energy for welding may be stored in a capacitor. *Percussion welding* (PEW) utilizes this technique, in which the power is discharged within 1 to 10 milliseconds to develop localized high heat at the joint. The process is useful where heating of the components adjacent to the joint is to be avoided, as in electronic assemblies and electrical wires.

EXAMPLE 31.3 Resistance Welding vs. Laser-beam Welding in the Can-making Industry

The cylindrical bodies of cans for food and for household products have been resistance seam welded (with a lap joint up the side of the can) for many years. Beginning in about 1987, laser-beam welding technology was introduced into the can-making industry. The joints are welded by lasers with the same productivity as in resistance welding, but with the following advantages:

- As opposed to the lap joints suitable for resistance welding, laser welding utilizes butt joints. Thus, some material is saved. Multiplied by the

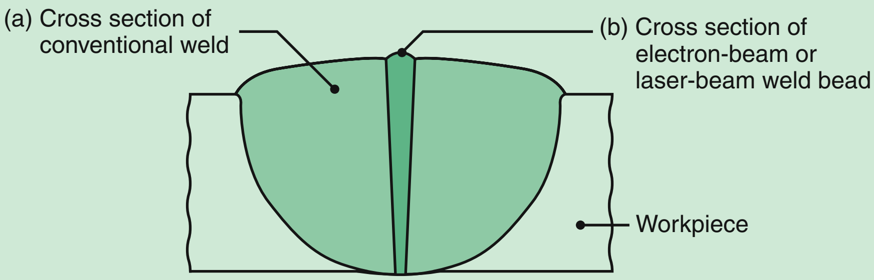

FIGURE 31.15 The relative sizes of the weld beads obtained by tungsten-arc and by electron-beam or laser-beam welding.

billions of cans made each year, this amount becomes a very significant savings.

- Because laser welds have a very narrow zone (Fig. 31.15; see also Fig. 30.14), the unprinted area on the can surface (the printing margin) is greatly reduced. As a result, the can's appearance and its customer acceptance are improved.
- The resistance lap-welded joint can be subject to corrosion by the contents of the can (e.g., tomato juice). This effect may change the taste and can cause a potential liability risk. A butt joint made by laser-beam welding eliminates the problem.

Source: Courtesy of G.F. Benedict.

31.6 Explosion Welding

In *explosion welding* (EXW), pressure is applied by detonating a layer of explosive that has been placed over one of the components being joined, called the *flyer plate* (Fig. 31.16a and b). The contact pressures developed are extremely high, and the kinetic energy of the plate striking the mating component causes a wavy interface.

This impact mechanically interlocks the two surfaces (Fig. 31.16c and d), so that pressure welding by plastic deformation also takes place. The flyer plate is placed at an angle, and any oxide films present at the interface are broken up and propelled out of the interface. As a result, the bond strength from explosion welding is very high.

The explosive may be a flexible plastic sheet or cord or in granulated or liquid form, which is cast or pressed onto the flyer plate. The detonation speed is usually in the range from 2400 to 3600 m/s (8000 to 12,000 ft/s); it depends on the type of explosive, the thickness of the explosive layer, and the packing density of the layer. There is a minimum denotation speed necessary for welding to occur in this process. Detonation is carried out with a standard commercial blasting cap.

This process is suitable particularly for cladding a plate or a slab with a dissimilar metal. Plates as large as 6×2 m (20×7 ft) have been clad explosively. They may then be rolled into thinner sections. Tubes and pipes can be joined to the holes in the header plates of boilers and heat exchangers by placing the explosive inside the tube; the explosion expands the tube. Explosion welding is inherently dangerous, so it requires safe handling by well-trained and experienced personnel.

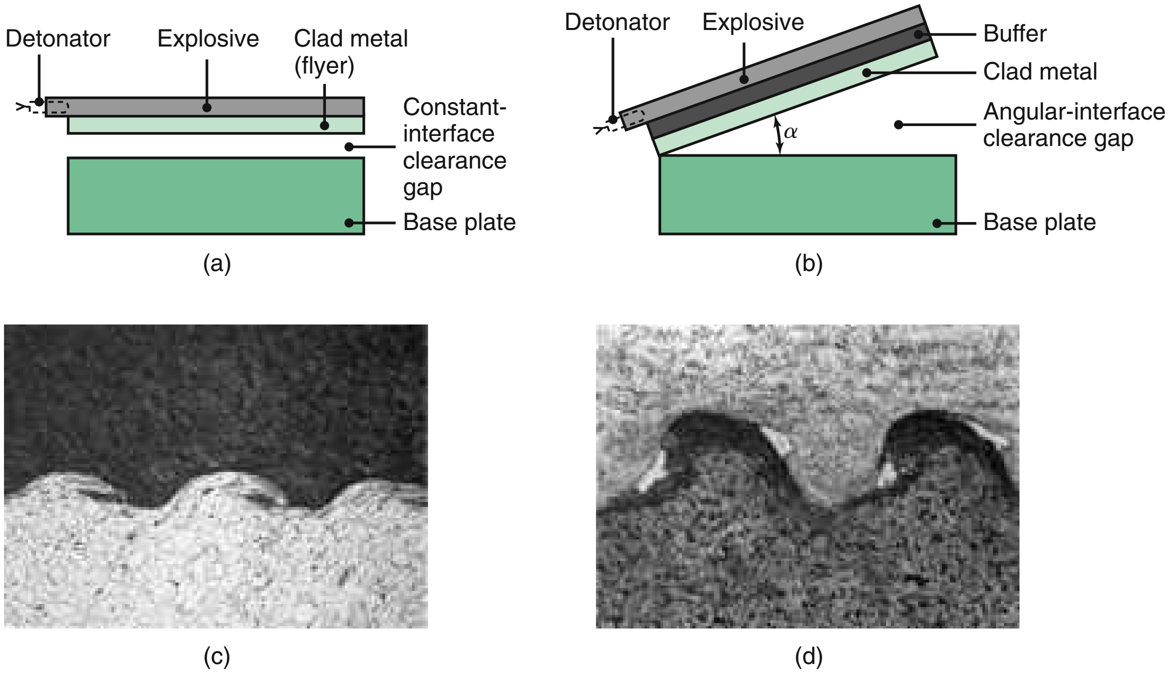

FIGURE 31.16 Schematic illustration of the explosion-welding process: (a) constant-interface clearance gap and (b) angular-interface clearance gap. (c) Cross section of explosion-welded joint: titanium (top) and low-carbon steel (bottom). (d) Iron–nickel alloy (top) and low-carbon steel (bottom).

31.7 Diffusion Bonding

Diffusion bonding, or **diffusion welding** (DFW) is a process in which the strength of the joint results primarily from diffusion (movement of atoms across the interface) and secondarily from plastic deformation of the faying surfaces. This process requires temperatures of about $0.5T_m$ (where T_m is the melting point of the metal on the absolute scale) in order to have a sufficiently high diffusion rate between the parts being joined. (See also Sections 1.7 and 1.8.)

The bonded interface in diffusion welding has essentially the same physical and mechanical properties as the base metal. Its strength depends on (a) pressure, (b) temperature, (c) time of contact, and (d) how clean the faying surfaces are. These requirements can be relaxed by using a filler metal at the interface. Depending on the materials joined, brittle intermetallic compounds may form at the interface. They may be avoided by electroplating the surfaces with suitable metal alloys.

In diffusion bonding, pressure may be applied by dead weights, a press, differential gas pressure, or the thermal expansion of the parts to be joined. The parts usually are heated in a furnace or by electrical resistance. High-pressure autoclaves also are used for bonding complex parts.

Although this process was developed in the 1970s as a modern welding technology, the principle of diffusion bonding dates back centuries to when goldsmiths bonded gold over copper to create a product called **filled gold**. First, a thin layer of gold foil is produced and placed over copper, and a weight is placed on top of the foil. Finally, the assembly is placed in a furnace and left until a strong bond is obtained; hence, the process is also called *hot-pressure welding* (HPW).

Diffusion bonding generally is most suitable for joining dissimilar metals. It also is used for reactive metals (such as titanium, beryllium, zirconium, and refractory metal alloys) and for composite materials such as metal-matrix composites (Section 9.5). Diffusion bonding is also an important mechanism of sintering in powder metallurgy (Section 17.4). Because diffusion involves migration of the atoms across the joint, the process is slower than other welding processes.

Although diffusion welding is used for fabricating complex parts in low quantities for the aerospace, nuclear, and electronics industries, it has been automated to make it suitable and economical for moderate-volume production. Unless the process is highly automated, considerable operator training and skill are required. Equipment cost is related approximately to the diffusion-bonded area and is in the range of \$3 to \$6/mm^2 (\$2000 to \$4000/in^2).

EXAMPLE 31.4 Diffusion-bonding Applications

Diffusion bonding is especially suitable for such metals as titanium and the superalloys used in military aircraft. Design possibilities allow the conservation of expensive strategic materials and the reduction of manufacturing costs. The military aircraft illustrated in Fig. 31.17 has more than 100 diffusion-bonded parts, some of which are shown.

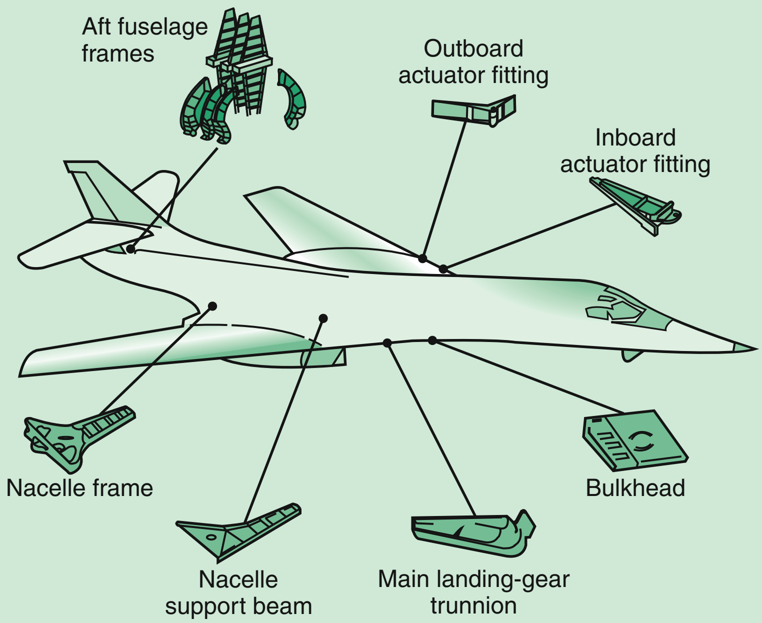

FIGURE 31.17 Aerospace diffusion bonding applications.

Diffusion Bonding–superplastic Forming. Sheet-metal structures can be fabricated by combining *diffusion bonding* with *superplastic forming* (see also Section 16.10). Typical structures in which flat sheets (usually) are diffusion bonded and formed are shown in Fig. 31.18. After the diffusion bonding of selected locations on the sheets, the unbonded (*stop-off*) regions are expanded in a mold by air or fluid pressure. These structures are thin and have high stiffness-to-weight ratios; hence, they are particularly useful in aircraft and aerospace applications.

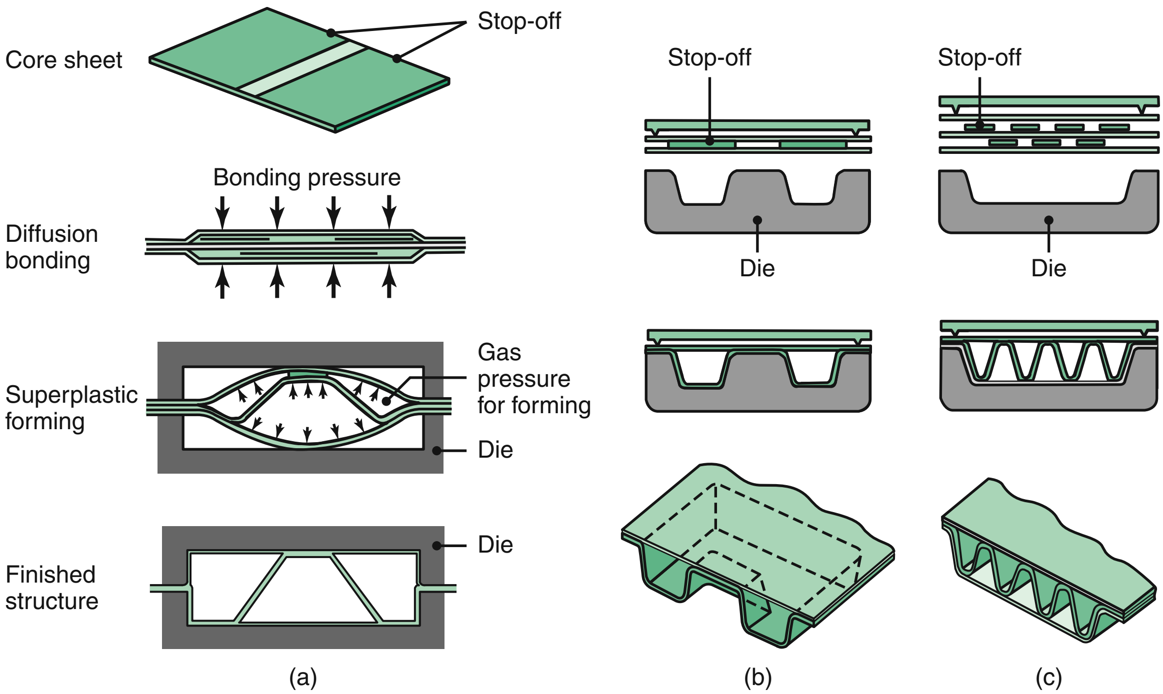

FIGURE 31.18 The sequence of operations in the fabrication of a structure by the diffusion bonding and superplastic forming of three originally flat sheets. See also Fig. 16.48. *Sources*: (a) After D. Stephen and S.J. Swadling. (b) and (c) Courtesy of Rockwell International Corp.

Diffusion bonding–superplastic forming improves productivity by eliminating the number of parts in a structure, mechanical fasteners, labor, and cost. It produces parts with good dimensional accuracy and low residual stresses. First developed in the 1970s, this technology is now well advanced for titanium structures (typically using Ti-6Al-4V and 7475-T6) and various other alloys for aerospace applications.

31.8 Economics of Welding Operations

The characteristics, advantages, and limitations of the welding processes described thus far have included brief discussions regarding welding costs. The relative costs of some selected processes are shown in Tables 30.1 and VI.1. As in all other manufacturing operations, costs in welding and joining processes can vary widely, depending on such factors as the equipment capacity, level of automation, labor skill required, weld quality, production rate, and preparation required, as well as on various other considerations specific to a particular joining process.

The general *welding and joining costs* for some common operations (all described throughout Chapters 30 through 32) can be summarized as follows:

- *High*: brazing and fasteners (such as bolts and nuts), as they require hole-making operations and fastener costs.
- *Intermediate*: arc welding, riveting, adhesive bonding.
- *Low*: resistance welding, seaming, and crimping, as these operations are relatively simple to perform and automate.