PART VI

Joining Processes and Equipment

When inspecting various common products, note that some products, such as paper clips, nails, steel balls for bearings, staples, screws and bolts, are made of only one component. Almost all products, however, are assembled from components that have been manufactured as individual parts. Even relatively simple products consist of at least two different components joined by various means. For example, (a) some kitchen knives have wooden or plastic handles that are attached to the metal blade with fasteners; (b) cooking pots and pans have metal, plastic, or wooden handles and knobs that are attached to the pot by various methods; and (c) the eraser of an ordinary pencil is attached with a brass sleeve.

On a much larger scale, observe power tools, washing machines, motorcycles, ships, and airplanes and how their numerous components are assembled and joined so that they not only can function reliably, but also are economical to produce. As shown in Table I.1 in the General Introduction, a rotary lawn mower has about 300 parts and a grand piano has 12,000 parts. A C-5A transport plane has more than 4 million parts, and a Boeing 747-400 aircraft has more than 6 million parts. A typical automobile consists of 15,000 components, some of which are shown in Fig. VI.1.

Joining is an all-inclusive term covering processes such as welding, brazing, soldering, adhesive bonding, and mechanical fastening. These processes are an essential

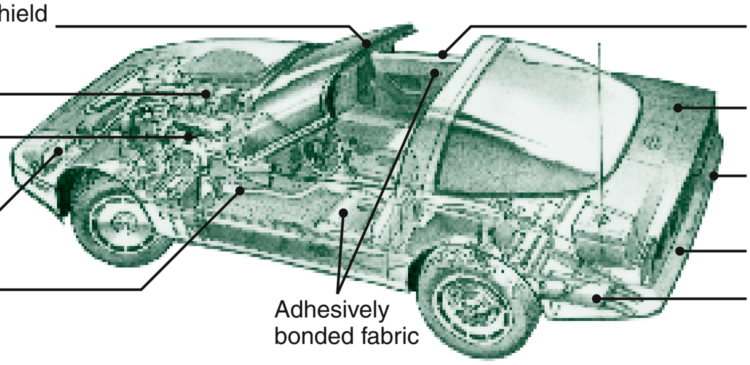


FIGURE VI.1 Various parts in a typical automobile that are assembled by the processes described in Part VI.

and important aspect of manufacturing and *assembly* operations, for one or more of the following reasons:

- Even a relatively simple product may be impossible to manufacture as a *single piece*. Consider, for example, the tubular construction shown in Fig. VI.2a. Assume that each of the arms of this product is 5 m (15 ft) long, the tubes are 100 mm (4 in.) in diameter, and their wall thickness is 1 mm (0.04 in.). After reviewing all of the manufacturing processes described in the preceding chapters, one would conclude that manufacturing this product in one piece would be impossible or uneconomical.
- The product, such as a cooking pot with a handle, is *easier and more economical* to manufacture as individual components, which are then assembled into a product.
- Products such as hair dryers, appliances, and automobile engines need to be designed to be able to be *taken apart* for maintenance or replacement of their parts.
- *Different properties* may be desirable for functional purposes of the product. For example, surfaces subjected to friction, wear, corrosion, or environmental attack generally require characteristics that differ significantly from those of the component's bulk. Examples are (a) masonry drills with carbide cutting tips brazed to the shank of a drill (Fig. VI.2b), (b) automotive brake shoes, and (c) grinding wheels bonded to a metal backing (Section 26.2).
- *Transporting* the product in individual components and assembling them later may be easier and less costly than transporting the completed item. Metal or wood shelving, large toys, and machinery are assembled after the components or subassemblies have been transported to the appropriate site.

Although there are different ways of categorizing the wide variety of available joining processes, we will follow the classification by the American Welding Society

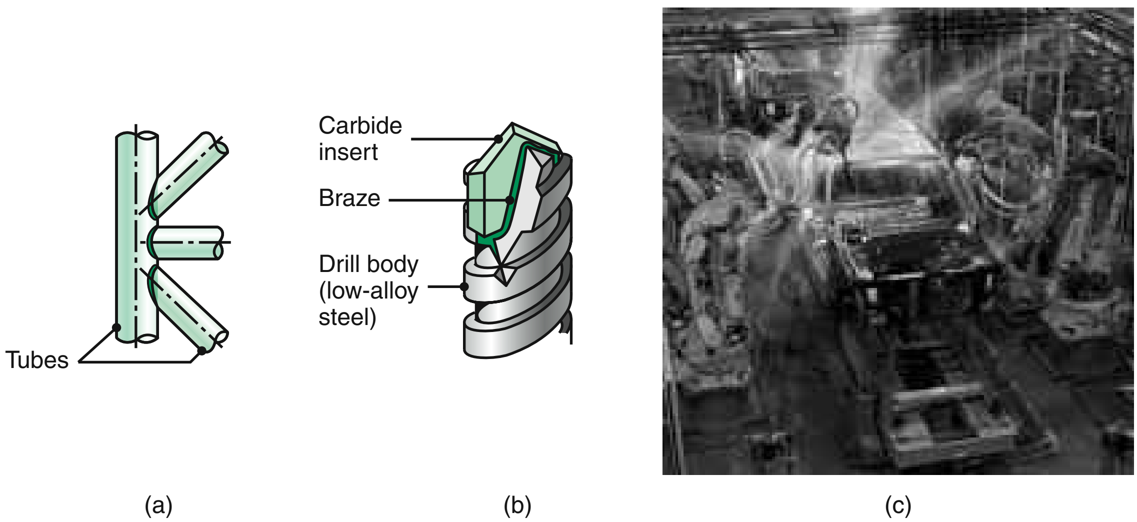


FIGURE VI.2 Examples of parts utilizing joining processes. (a) A tubular part fabricated by joining individual components. This product cannot be manufactured in one piece by any of the methods described in the previous chapters if it consists of thin-walled, large-diameter, tubular-shaped long arms. (b) A drill bit with a carbide cutting insert brazed to a steel shank—an example of a part in which two materials need to be joined for performance reasons. (c) Spot welding of automobile bodies. *Source*: (c) Courtesy of Ford Motor Co.

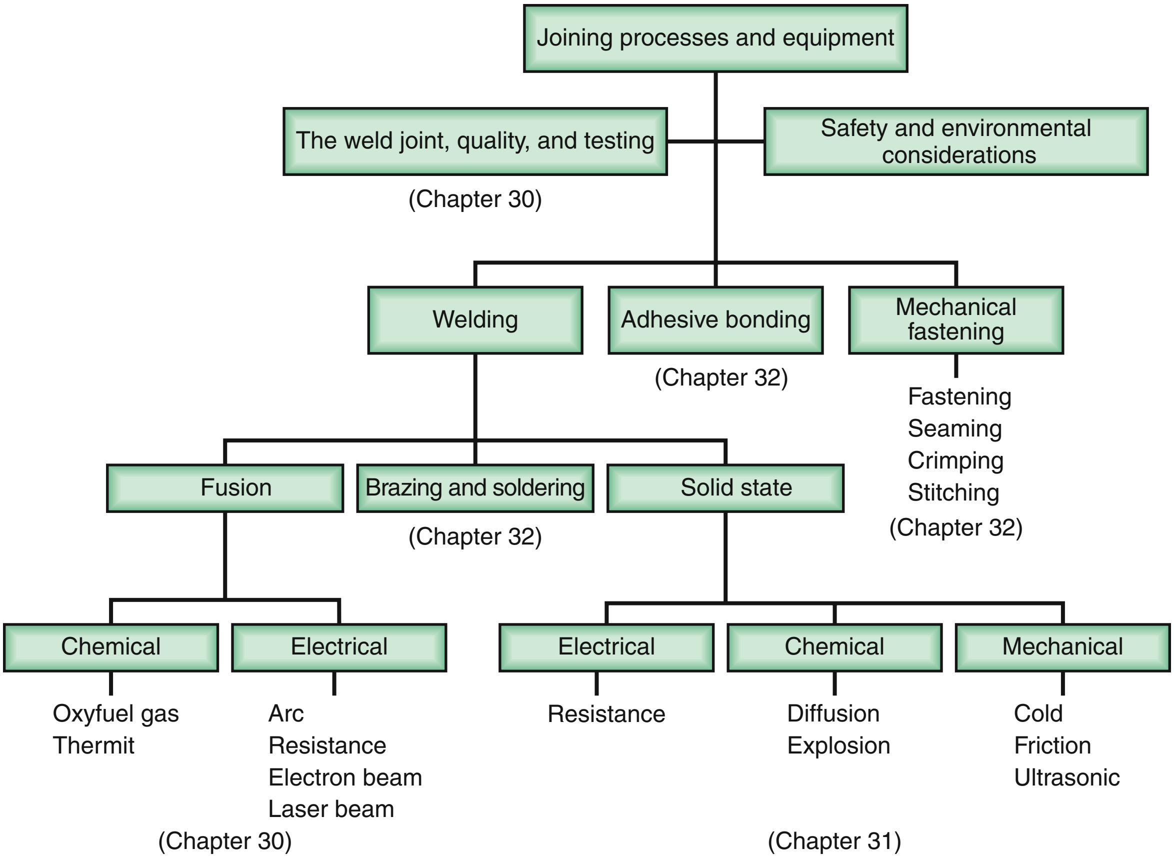


FIGURE VI.3 Outline of topics described in Part VI.

(AWS). Accordingly, joining processes fall into three major categories (see Figs. VI.3 and I.7f):

- **Welding**
- **Adhesive bonding**
- **Mechanical fastening.**

Table VI.1 lists the general relative characteristics of various joining processes. Welding processes, in turn, are generally classified into three basic categories:

- **Fusion welding**
- **Solid-state welding**
- **Brazing and soldering.**

As will be seen, some types of welding processes can be classified into both the fusion and the solid-state categories.

Fusion welding is defined as the *melting together and coalescing* of materials by means of heat, usually supplied by chemical or electrical means; filler metals may or may not be used. Fusion welding is composed of consumable- and nonconsumable-electrode arc welding and high-energy-beam welding processes. The welded joint undergoes important metallurgical and physical changes, which, in turn, have a major

TABLE VI.1

Comparison of Various Joining Methods

	Characteristics								
Method	Strength	Design	Small parts	Large parts	Tolerances	Reliability	Ease of manufacture	Ease of inspection	Cost
Arc welding	1	2	3	1	3	1	2	2	2
Resistance welding	1	2	1	1	3	3	3	3	1
Brazing	1	1	1	1	3	1	3	2	3
Bolts and nuts	1	2	3	1	2	1	1	1	3
Riveting	1	2	3	1	1	1	3	1	2
Fasteners	2	3	3	1	2	2	2	1	3
Seaming and crimping	2	2	1	3	3	1	3	1	1
Adhesive bonding	3	1	1	2	3	2	3	3	2

Note: 1 = very good; 2 = good; 3 = poor. For cost, 1 is the lowest.

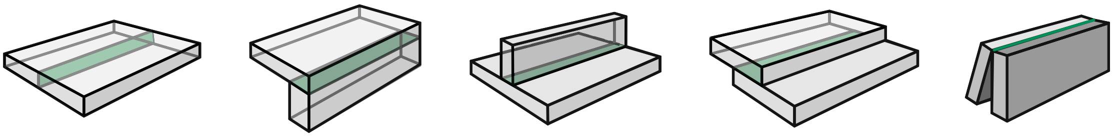


FIGURE VI.4 Examples of joints that can be made through the various joining processes described in Chapters 30 through 32.

effect on the properties and performance of the welded component or structure. Some simple welded joints are shown in Fig. VI.4.

In **solid-state welding**, joining takes place *without fusion*; consequently, there is no liquid (molten) phase in the joint. The basic processes in this category are diffusion bonding and cold, ultrasonic, friction, resistance, and explosion welding. **Brazing** uses filler metals and involves lower temperatures than welding. **Soldering** uses similar filler metals (solders) and involves even lower temperatures.

Adhesive bonding has unique applications that require strength, sealing, thermal and electrical insulating, vibration damping, and resistance to corrosion between dissimilar metals. **Mechanical fastening** involves traditional methods of using various fasteners, especially bolts, nuts, and rivets. The **joining of plastics** can be accomplished by adhesive bonding, fusion by various external or internal heat sources, and mechanical fastening.

Fusion-Welding Processes

CHAPTER 30

- This chapter describes fusion-welding processes, in which two pieces are joined together by the application of heat, which melts and fuses the interface; the operation is sometimes assisted with a filler metal.
- All fusion-welding processes are discussed in this chapter, beginning with oxyfuel–gas welding, in which acetylene and oxygen provide the energy for welding.
- Various arc-welding processes are then described, in which electrical energy and consumable or nonconsumable electrodes are used to produce the weld; specific processes examined include shielded metal arc welding, flux-cored arc welding, gas tungsten-arc welding, submerged arc welding, and gas metal-arc welding.
- Welding with high-energy beams is then discussed, in which electron beams or lasers provide highly focused heat sources.
- The chapter ends with a discussion of the weld joint, including quality, inspection, and testing procedures, along with a discussion of good weld design practices and process selection.

EXAMPLES:

30.1 Introduction

The welding processes described in this chapter involve the partial melting and fusion between two members to be joined. Here, **fusion welding** is defined as *melting together and coalescing* materials by means of heat. *Filler metals*, which are metals added to the weld area during welding, also may be used. Fusion welds made without the use of filler metals are known as *autogenous welds*.

The chapter describes the major classes of fusion-welding processes. It covers the basic principles of each process; the equipment used; the relative advantages, limitations, and capabilities of the process; and the economic considerations affecting process selection (Table 30.1). These processes include the oxyfuel–gas, arc, and high-energy-beam (laser-beam and electron-beam) welding processes, which have important and unique applications in modern manufacturing.

The chapter continues with a description of weld-zone features and the variety of discontinuities and defects that can exist in welded joints. The weldability of

TABLE 30.1

General Characteristics of Fusion-welding Processes

Joining process	Operation	Advantage	Skill level required	Welding position	Current type	Distortion*	Typical cost of equipment ($)
Shielded metal arc	Manual	Portable and flexible	High	All	AC, DC	1 to 2	Low (1500+)
Submerged arc	Automatic	High deposition	Low to medium	Flat and horizontal	AC, DC	1 to 2	Medium (5000+)
Gas metal arc	Semiautomatic or automatic	Most metals	Low to high	All	DC	2 to 3	Medium (3000+)
Gas tungsten arc	Manual or automatic	Most metals	Low to high	All	AC, DC	2 to 3	Medium (5000+)
Flux-cored arc	Semiautomatic or automatic	High deposition	Low to high	All	DC	1 to 3	Medium (2000+)
Oxyfuel	Manual	Portable and flexible	High	All	—	2 to 4	Low (500+)
Electron beam, laser beam	Semiautomatic or automatic	Most metals	Medium to high	All	—	3 to 5	High (100,000–1 million)

*1 = highest; 5 = lowest.

various ferrous and nonferrous metals and alloys are then reviewed. The chapter ends with a discussion of design guidelines for welding, giving several examples of good weld-design practices. As in all manufacturing processes, the economics of welding is a significant aspect of the overall operation. Welding processes, equipment, and labor costs are discussed in Section 31.8.

30.2 Oxyfuel–gas Welding

Oxyfuel–gas welding (OFW) is a general term used to describe any welding process that uses a **fuel gas** combined with *oxygen* to produce a flame. The flame is the source of the heat that is used to melt the metals at the joint. The most common gas-welding process uses *acetylene*; the process is known as *oxyacetylene–gas welding* (OAW) and is typically used for structural metal fabrication and repair work.

Developed in the early 1900s, OAW utilizes the heat generated by the combustion of acetylene gas (C_2H_2) in a mixture with oxygen. The heat is generated in accordance with a pair of chemical reactions. The primary combustion process, which occurs in the inner core of the flame (Fig. 30.1), involves the following reaction:

$$C_2H_2 + O_2 \longrightarrow 2CO + H_2 + \text{Heat}. \tag{30.1}$$

This reaction dissociates the acetylene into carbon monoxide and hydrogen and produces about one-third of the total heat generated in the flame. The secondary combustion process is

$$2CO + H_2 + 1.5O_2 \longrightarrow 2CO_2 + H_2O + \text{Heat}. \tag{30.2}$$

This reaction consists of the further burning of both the hydrogen and the carbon monoxide and produces about two-thirds of the total heat. Note that the reaction also produces water vapor. The temperatures developed in the flame can reach 3300°C (6000°F).

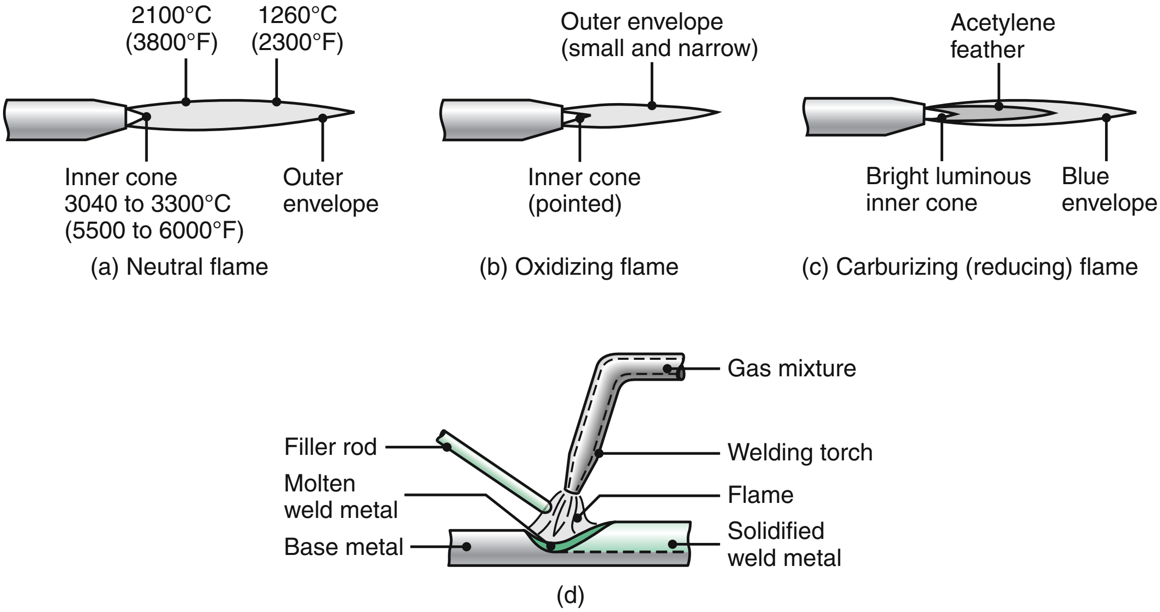


FIGURE 30.1 Three basic types of oxyacetylene flames used in oxyfuel–gas welding and cutting operations: (a) neutral flame; (b) oxidizing flame; (c) carburizing, or reducing, flame. The gas mixture in (a) is basically equal volumes of oxygen and acetylene. (d) The principle of the oxyfuel–gas welding process.

Flame Types. The proportion of acetylene and oxygen in the gas mixture is an important factor in oxyfuel–gas welding. At a ratio of 1:1 (i.e., when there is no excess oxygen), the flame is considered to be *neutral* (Fig. 30.1a). With a greater oxygen supply, the flame can be harmful (especially for steels), because it oxidizes the metal. For this reason, a flame with excess oxygen is known as an **oxidizing flame** (Fig. 30.1b). Only in the welding of copper and copper-based alloys is an oxidizing flame desirable, because in those cases, a thin protective layer of *slag* (compounds of oxides) forms over the molten metal. If the oxygen is insufficient for full combustion, the flame is known as a **reducing**, or **carburizing, flame** (a flame having excess acetylene; Fig. 30.1c). The temperature of a reducing flame is lower; hence, such a flame is suitable for applications requiring low heat, such as brazing, soldering, and flame-hardening operations.

Other fuel gases (such as hydrogen and methylacetylene propadiene) also can be used in oxyfuel–gas welding. However, the temperatures developed by these gases are lower than those produced by acetylene. Hence, they are used for welding (a) metals with low melting points (such as lead) and (b) parts that are thin and small. The flame with pure hydrogen gas is colorless; therefore, it is difficult to adjust the flame by eyesight.

Filler Metals. Filler metals are used to supply additional metal to the weld zone during welding. They are available as **filler rods** or *wire* (Fig. 30.1d) and may be bare or coated with **flux**. The purpose of the flux is to retard oxidation of the surfaces of the parts being welded by generating a *gaseous shield* around the weld zone. The flux also helps to dissolve and remove oxides and other substances from the weld zone, thus contributing to the formation of a stronger joint. The slag developed (compounds of oxides, fluxes, and electrode-coating materials) protects the molten puddle of metal against oxidation as it cools.

Welding Practice and Equipment. Oxyfuel–gas welding can be used with most ferrous and nonferrous metals for almost any workpiece thickness, but the relatively low heat input limits the process to thicknesses of less than 6 mm (0.25 in.).

Small joints made by this process may consist of a single-weld bead. Deep-V groove joints are made in multiple passes. Cleaning the surface of each weld bead prior to depositing a second layer is important for joint strength and in avoiding defects (see Section 30.9). Wire brushes (hand or power) may be used for this purpose.

The equipment for oxyfuel–gas welding consists basically of a **welding torch** connected by hoses to high-pressure gas cylinders and equipped with pressure gages and regulators (Fig. 30.2). The use of safety equipment (such as goggles with shaded lenses, face shields, gloves, and protective clothing) is essential. Proper connection of the hoses to the cylinders is an important factor in safety. Oxygen and acetylene cylinders have different threads, so the hoses cannot be connected to the wrong cylinders. The low equipment cost is an attractive feature of oxyfuel–gas welding. Although it can be mechanized, this operation is essentially manual and, hence,

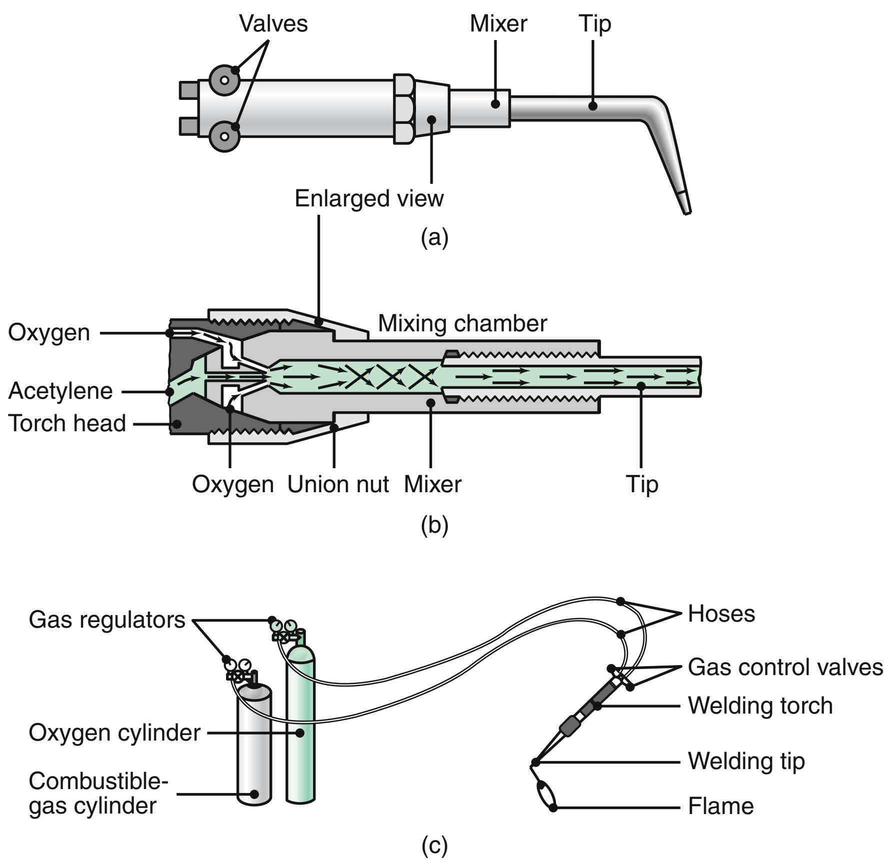


FIGURE 30.2 (a) General view of, and (b) cross section of, a torch used in oxyacetylene welding. The acetylene valve is opened first. The gas is lit with a spark lighter or a pilot light. Then the oxygen valve is opened and the flame adjusted. (c) Basic equipment used in oxyfuel–gas welding. To ensure correct connections, all threads on acetylene fittings are left handed, whereas those for oxygen are right handed. Oxygen regulators usually are painted green and acetylene regulators red.

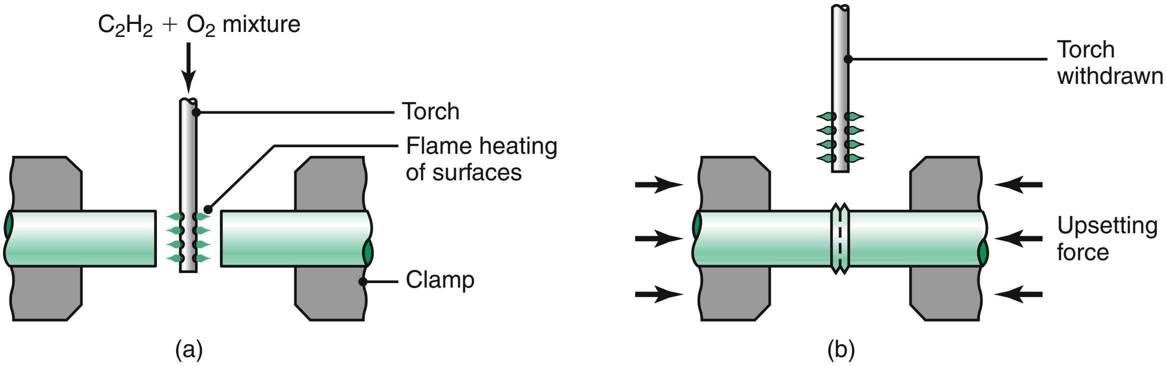


FIGURE 30.3 Schematic illustration of the pressure-gas welding process: (a) before and (b) after. Note the formation of a flash at the joint; later the flash can be trimmed off.

slow. However, it has the advantages of being portable, versatile, and economical for simple and low-quantity work.

Pressure-gas Welding. In this method, the welding of two components starts with the heating of the interface by means of a torch using (typically) an oxyacetylene–gas mixture (Fig. 30.3a). After the interface begins to melt, the torch is withdrawn. A force is applied to press the two components together (Fig. 30.3b) and is maintained until the interface solidifies. Note the formation of a flash due to the upsetting of the joined ends of the two components.

30.3 Arc-welding Processes: Nonconsumable Electrode

In *arc welding*, developed in the mid-1800s, the heat required is obtained from electrical energy. The process involves either a *consumable* or a *nonconsumable electrode*. An AC or a DC power supply produces an arc between the tip of the electrode and the workpiece to be welded. The arc generates temperatures of about 30,000°C (54,000°F), which are much higher than those developed in oxyfuel–gas welding.

In *nonconsumable-electrode* welding processes, the electrode is typically a **tungsten electrode** (Fig. 30.4). Because of the high temperatures involved, an externally supplied shielding gas is necessary to prevent oxidation of the weld zone. Typically, direct current is used, and its **polarity** (the direction of current flow) is important. The selection of current levels depends on such factors as the type of electrode, metals to be welded, and depth and width of the weld zone.

In **straight polarity**—also known as *direct-current electrode negative* (DCEN)—the workpiece is positive (anode), and the electrode is negative (cathode). DCEN generally produces welds that are narrow and deep (Fig. 30.5a). In **reverse polarity**—also known as *direct-current electrode positive* (DCEP)—the workpiece is negative and the electrode is positive. Weld penetration is less, and the weld zone is shallower and wider (Fig. 30.5b). Hence, DCEP is preferred for sheet metals and for joints with very wide gaps. In the **AC current** method, the arc pulsates rapidly. This method is suitable for welding thick sections and for using large-diameter electrodes at maximum currents (Fig. 30.5c).

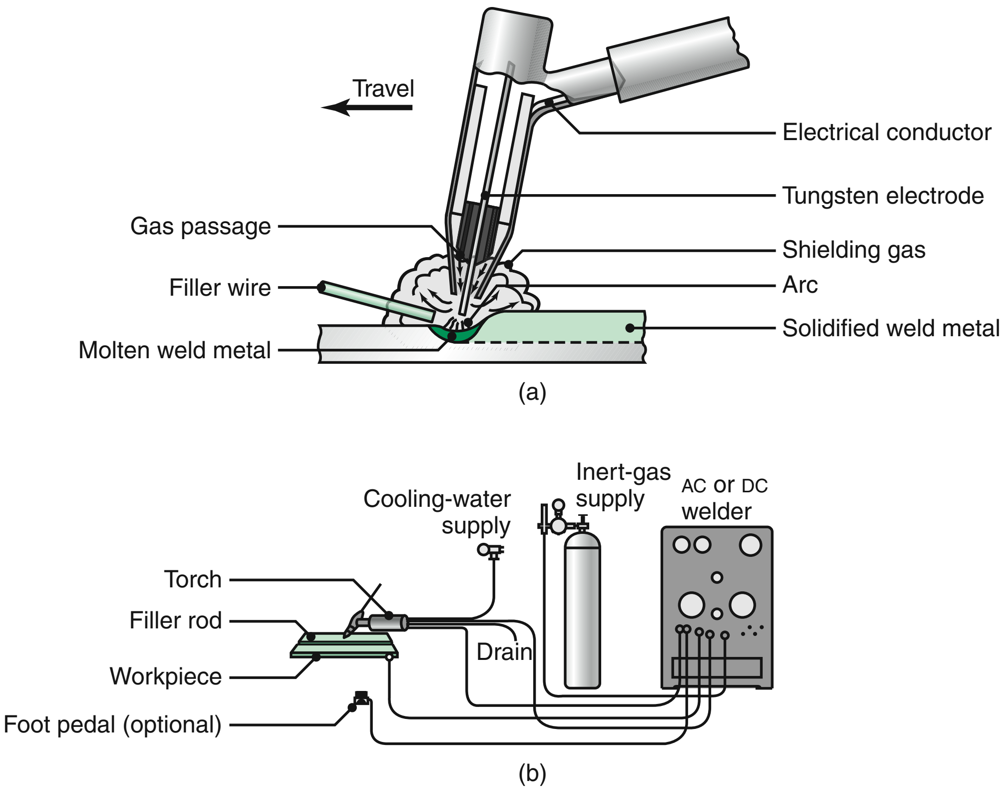


FIGURE 30.4 (a) The gas tungsten-arc welding process, formerly known as TIG (for tungsten–inert-gas) welding. (b) Equipment for gas tungsten-arc welding operations.

Heat Transfer in Arc Welding. The heat input in arc welding is given by the equation

$$\frac{H}{l} = e\frac{VI}{v}, \tag{30.3}$$

where H is the heat input (J or BTU), l is the weld length, V is the voltage applied, I is the current (amperes), and v is the welding speed. The term e is the efficiency of the process and varies from around 75% for shielded metal-arc welding to 90% for gas metal-arc welding and submerged-arc welding. The efficiency is an indication that not all of the available energy is beneficially used to melt material, because the heat is conducted through the workpiece, some is lost by radiation, and still more is lost by convection to the surrounding environment.

The heat input given by Eq. (30.3) melts a certain volume of material, usually the electrode or filler metal, and can also be expressed as

$$H = uV_m = uAl, \tag{30.4}$$

where u is the specific energy required for melting, V_m is the volume of material melted, and A is the cross section of the weld. Some typical values of u are given in Table 30.2. Equations (30.3) and (30.4) allow an expression of the welding speed:

$$v = e\frac{VI}{uA}. \tag{30.5}$$

Although these equations have been developed for arc welding, similar ones can be obtained for other fusion-welding operations as well, taking into account differences in weld geometry and process efficiency.

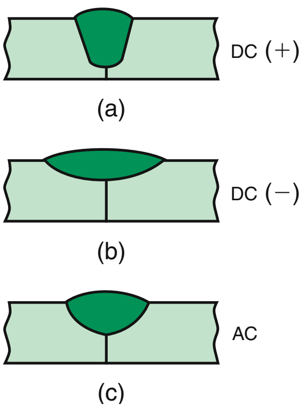


FIGURE 30.5 The effect of polarity and current type on weld beads: (a) DC current with straight polarity; (b) DC current with reverse polarity; (c) AC current.

TABLE 30.2

Approximate Specific Energies Required to Melt a Unit Volume of Commonly Welded Metals

Material	Specific energy, u J/mm^3	BTU/in^3
Aluminum and its alloys	2.9	41
Cast irons	7.8	112
Copper	6.1	87
Bronze (90Cu–10Sn)	4.2	59
Magnesium	2.9	42
Nickel	9.8	142
Steels	9.1–10.3	128–146
Stainless steels	9.3–9.6	133–137
Titanium	14.3	204

Note: 1 BTU = 1055 J = 778 ft-lb.

EXAMPLE 30.1 Welding Speed for Different Materials

Consider a situation in which a welding operation is being performed with $V = 20$ volts, $I = 200$ A, and the cross-sectional area of the weld bead is 30 mm^2. Estimate the welding speed if the workpiece and electrode are made of (a) aluminum, (b) carbon steel, and (c) titanium. Use an efficiency of 75%.

Solution For aluminum, we note from Table 30.2 that the specific energy required is $u = 2.9$ J/mm^3. Therefore, from Eq. (30.5),

$$v = e\frac{VI}{uA} = (0.75)\frac{(20)(200)}{(2.9)(30)} = 34.5 \text{ mm/s}.$$

Similarly, for carbon steel, u is estimated as 9.7 J/mm^3 (average of extreme values in the table), leading to $v = 10.3$ mm/s. For titanium, $u = 14.3$ J/mm^3, so that $v = 7.0$ mm/s.

Gas Tungsten-arc Welding. In *gas tungsten-arc welding* (GTAW), formerly known as *TIG* (for "tungsten inert gas") *welding*, the filler metal is supplied from a **filler wire** (Fig. 30.4a). Because the tungsten electrode is not consumed in this operation, a constant and stable *arc gap* is maintained at a constant current level. The filler metals are similar to the metals to be welded, and flux is not used. The shielding gas is usually argon or helium (or a mixture of the two). Welding with GTAW may be done without filler metals—for example, in the welding of close-fit joints.

Depending on the metals to be welded, the power supply is either DC at 200 A or AC at 500 A (Fig. 30.4b). In general, AC is preferred for aluminum and magnesium, because the cleaning action of AC removes oxides and improves weld quality. Thorium or zirconium may be used in the tungsten electrodes to improve their electron emission characteristics. The power supply ranges from 8 to 20 kW. Contamination of the tungsten electrode by the molten metal can be a significant problem, particularly in critical applications, because it can cause discontinuities in the weld. Therefore, contact of the electrode with the molten-metal pool should be avoided.

The GTAW process is used for a wide variety of applications and metals, particularly aluminum, magnesium, titanium, and the refractory metals. It is especially suitable for thin metals. The cost of the inert gas makes this process more expensive than SMAW, but provides welds of very high quality and surface finish. GTAW is used in a variety of critical applications with a wide range of workpiece thicknesses and shapes. The equipment is portable.

Plasma-arc Welding. In *plasma-arc welding* (PAW), developed in the 1960s, a concentrated plasma arc is produced and directed towards the weld area. The arc is stable and reaches temperatures as high as 33,000°C (60,000°F). A **plasma** is an ionized hot gas composed of nearly equal numbers of electrons and ions. The plasma is initiated between the tungsten electrode and the orifice by a low-current pilot arc. What makes plasma-arc welding unlike other processes is that the plasma arc is concentrated because it is forced through a relatively small orifice. Operating currents usually are below 100 A, but they can be higher for special applications. When a filler metal is used, it is fed into the arc, as is done in GTAW. Arc and weld-zone shielding is supplied by means of an outer-shielding ring and the use of gases such as argon, helium, or mixtures.

There are two methods of plasma-arc welding:

- In the **transferred-arc** method (Fig. 30.6a), the workpiece being welded is part of the electrical circuit. The arc transfers from the electrode to the workpiece—hence the term *transferred*.
- In the **nontransferred** method (Fig. 30.6b), the arc occurs between the electrode and the nozzle, and the heat is carried to the workpiece by the plasma gas. This thermal-transfer mechanism is similar to that for an oxyfuel flame (see Section 30.2).

Compared with other arc-welding processes, plasma-arc welding has better arc stability, less thermal distortion, and higher energy concentration, thus permitting deeper and narrower welds. In addition, higher welding speeds, from 120 to 1000 mm/min (5 to 40 in./min), can be achieved. A variety of metals can be welded with part thicknesses generally less than 6 mm (0.25 in.).

The high heat concentration can penetrate completely through the joint (known as the **keyhole technique**), with thicknesses as much as 20 mm (0.75 in.) for some titanium and aluminum alloys. In the keyhole technique, the force of the plasma arc displaces the molten metal and produces a hole at the leading edge of the weld pool. Plasma-arc welding (rather than the GTAW process) often is used for butt and lap joints because of its higher energy concentration, better arc stability, and higher welding speeds. Proper training and skill are essential for operators who

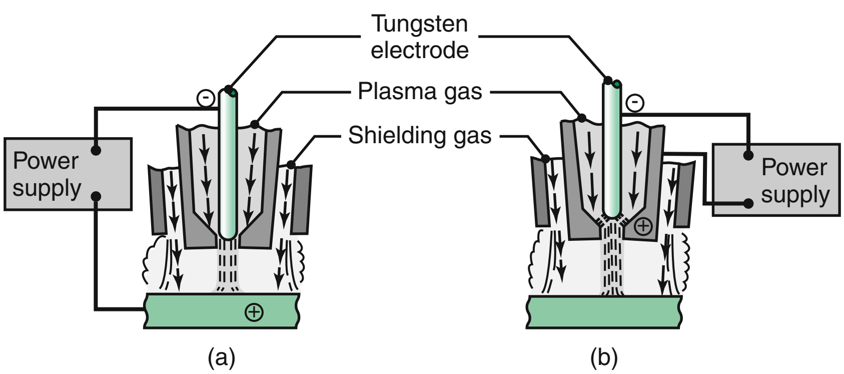


FIGURE 30.6 Two types of plasma-arc welding processes: (a) transferred and (b) nontransferred. Deep and narrow welds can be made by these processes at high welding speeds.

use this equipment. Safety considerations include protection against glare, spatter, and noise from the plasma arc.

Atomic-hydrogen Welding. In *atomic-hydrogen welding* (AHW), an arc is generated between two tungsten electrodes in a shielding atmosphere of hydrogen gas. The arc is maintained independently of the workpiece or parts being welded. The hydrogen gas normally is diatomic (H_2), but where the temperatures are over 6,000°C (11,000°F) near the arc, the hydrogen breaks down into its atomic form, simultaneously absorbing a large amount of heat from the arc. When the hydrogen strikes the cold surface of the workpieces to be joined, it recombines into its diatomic form and rapidly releases the stored heat. The energy in AHW can be varied easily by changing the distance between the arc stream and the workpiece surface. This process is being replaced by shielded metal-arc welding, mainly because of the availability of inexpensive inert gases.

30.4 Arc-welding Processes: Consumable Electrode

There are several consumable-electrode arc-welding processes.

30.4.1 Shielded Metal-arc Welding

Shielded metal-arc welding (SMAW) is one of the oldest, simplest, and most versatile joining processes. About 50% of all industrial and maintenance welding currently is performed by this process. The electric arc is generated by touching the tip of a *coated electrode* against the workpiece and withdrawing it quickly to a distance sufficient to maintain the arc (Fig. 30.7a). The electrodes are in the shapes of thin, long rods (hence, this process also is known as **stick welding**) that are held manually.

The heat generated melts a portion of the electrode tip, its coating, and the base metal in the immediate arc area. The molten metal consists of a mixture of the base metal (the workpiece), the electrode metal, and substances from the coating on the electrode; this mixture forms the weld when it solidifies. The electrode coating deoxidizes the weld area and provides a shielding gas to protect it from oxygen in the environment.

A bare section at the end of the electrode is clamped to one terminal of the power source, while the other terminal is connected to the workpiece being welded (Fig. 30.7b). The current, which may be DC or AC, usually ranges from 50 to 300 A.

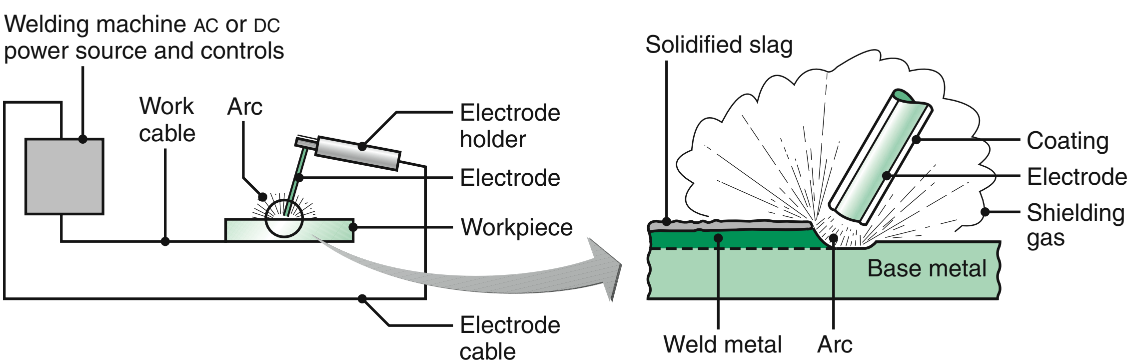


FIGURE 30.7 Schematic illustration of the shielded metal-arc welding process. About 50% of all large-scale industrial-welding operations use this process.

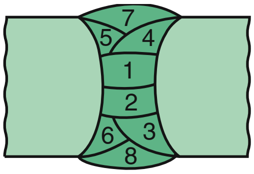


FIGURE 30.8 A deep weld showing the buildup sequence of eight individual weld beads.

For sheet-metal welding, DC is preferred because of the steady arc it produces. Power requirements generally are less than 10 kW.

The SMAW process has the advantages of being relatively simple, versatile, and requiring a smaller variety of electrodes. The equipment consists of a power supply, cables, and an electrode holder. The SMAW process commonly is used in general construction, shipbuilding, pipelines, and maintenance work. It is especially useful for work in remote areas where a portable fuel-powered generator can be used as the power supply. SMAW is best suited for workpiece thicknesses of 3 to 19 mm (0.12 to 0.75 in.), although this range can be extended easily by skilled operators using multiple-pass techniques (Fig. 30.8).

The multiple-pass approach requires that the slag be removed after each weld bead. Unless removed completely, the solidified slag can cause severe corrosion of the weld area and lead to failure of the weld, but it also prevents the fusion of weld layers and, therefore, compromises the weld strength. Before another weld is applied, the slag should be removed completely—for example, by wire brushing or weld chipping. Consequently, both labor costs and material costs are high.

30.4.2 Submerged-arc Welding

In *submerged-arc welding* (SAW), the weld arc is shielded by a *granular flux* consisting of lime, silica, manganese oxide, calcium fluoride, and other compounds. The flux is fed into the weld zone from a hopper by gravity flow through a nozzle (Fig. 30.9). The thick layer of flux completely covers the molten metal. It prevents spatter and sparks and suppresses the intense ultraviolet radiation and fumes characteristic of the SMAW process. The flux also acts as a thermal insulator by promoting deep penetration of heat into the workpiece. The unused flux can be recovered (using a recovery tube), treated, and reused.

The consumable electrode is a coil of bare round wire 1.5 to 10 mm ($\frac{1}{16}$ to $\frac{3}{8}$ in.) in diameter; it is fed automatically through a tube (**welding gun**). Electric currents typically range from 300 to 2000 A. The power supplies usually are connected to standard single- or three-phase power lines with a primary rating up to 440 V.

Because the flux is gravity fed, the SAW process is limited largely to welds in a flat or horizontal position having a backup piece. Circular welds can be made on pipes and cylinders—provided that they are rotated during welding. As Fig. 30.9 shows, the unfused flux can be recovered, treated, and reused. SAW is automated

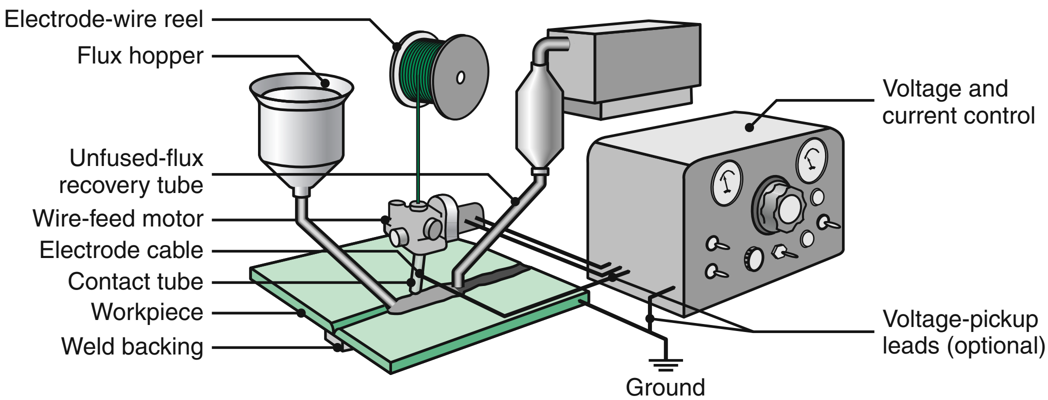


FIGURE 30.9 Schematic illustration of the submerged-arc welding process and equipment. The unfused flux is recovered and reused.

and is used to weld a variety of carbon and alloy steel and stainless-steel sheets or plates at speeds as high as 5 m/min (16 ft/min). The quality of the weld is very high—with good toughness, ductility, and uniformity of properties. The SAW process provides very high welding productivity, depositing 4 to 10 times the amount of weld metal per hour as the SMAW process. Typical applications include thick-plate welding for shipbuilding and for pressure vessels.

30.4.3 Gas Metal-arc Welding

In *gas metal-arc welding* (GMAW), developed in the 1950s and formerly called *metal inert-gas* (MIG) *welding*, the weld area is shielded by an effectively inert atmosphere of argon, helium, carbon dioxide, or various other gas mixtures (Fig. 30.10a). The consumable bare wire is fed automatically through a nozzle into the weld arc by a wire-feed drive motor (Fig. 30.10b). In addition to using inert shielding gases, deoxidizers usually are present in the electrode metal itself in order to prevent oxidation of the molten-weld puddle. Multiple-weld layers can be deposited at the joint.

Metal can be transferred by three methods in the GMAW process:

1. In **spray transfer**, small, molten metal droplets from the electrode are transferred to the weld area at a rate of several hundred droplets per second. The

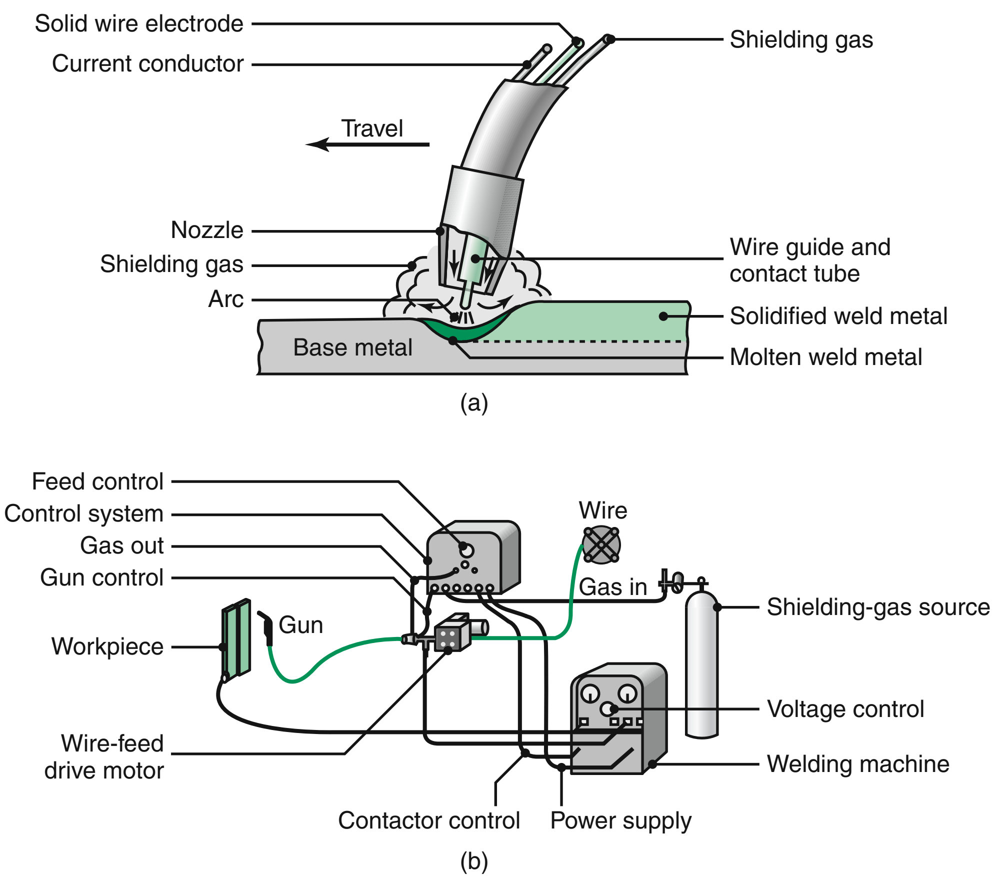


FIGURE 30.10 (a) Schematic illustration of the gas metal-arc welding process, formerly known as MIG (for metal inert-gas) welding. (b) Basic equipment used in gas metal-arc welding operations.

transfer is spatter free and very stable. High DC currents and voltages and large-diameter electrodes are used with argon or an argon-rich gas mixture as the shielding gas. The average current required in this process can be reduced with the use of a **pulsed arc**, which superimposes high-amplitude pulses onto a low, steady current. The process can be used in all welding positions.

2. In **globular transfer**, carbon-dioxide-rich gases are utilized, and globules are propelled by the forces of the electric-arc transfer of the metal, resulting in considerable spatter. High welding currents are used, making it possible for greater weld penetration and higher welding speed than are achieved in spray transfer. Heavier sections commonly are joined by this method.
3. In **short circuiting**, the metal is transferred in individual droplets (more than 50 per second) as the electrode tip touches the molten weld metal and short-circuits. Low currents and voltages are utilized with carbon-dioxide-rich gases and electrodes made of small-diameter wire. The power required is about 2 kW.

The temperatures generated in GMAW are relatively low; consequently, this method is suitable only for thin sheets and sections of less than 6 mm (0.25 in.); otherwise incomplete fusion may occur. The operation, which is easy to perform, is commonly used for welding ferrous metals in thin sections. Pulsed-arc systems are used for thin ferrous and nonferrous metals.

The GMAW process is suitable for welding most ferrous and nonferrous metals and is used extensively in the metal-fabrication industry. Because of the relatively simple nature of the process, the training of operators is easy. The process is versatile, rapid, and economical, and welding productivity is double that of the SMAW process. The GMAW process can be automated easily and lends itself readily to robotics and to flexible manufacturing systems (see Chapters 37 and 39).

30.4.4 Flux-cored Arc Welding

The *flux-cored arc welding* (FCAW) process, illustrated in Fig. 30.11, is similar to gas metal-arc welding, except that the electrode is tubular in shape and is filled with

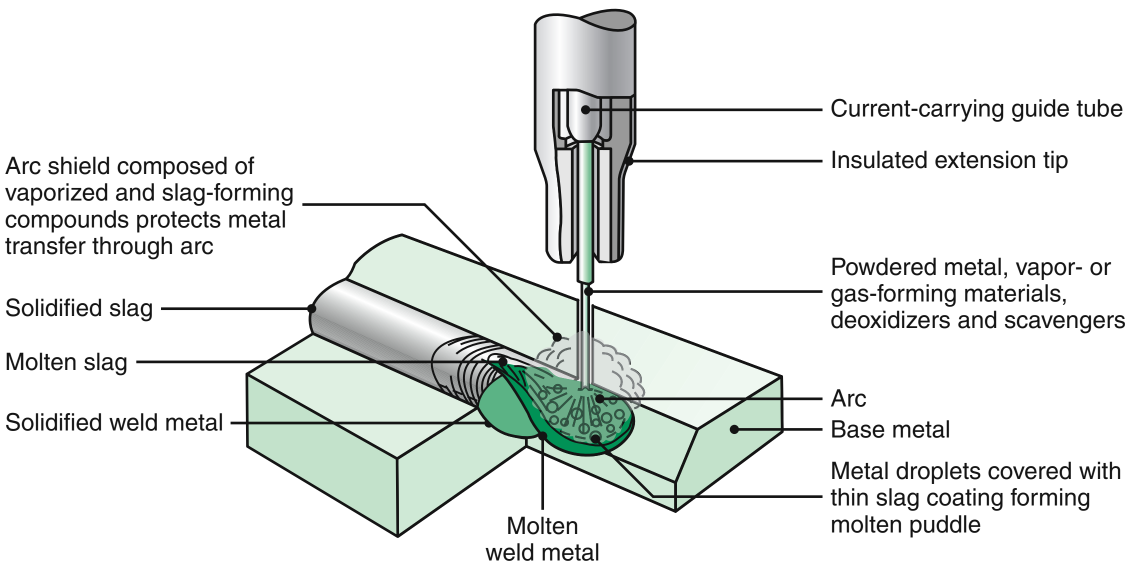


FIGURE 30.11 Schematic illustration of the flux-cored arc-welding process. This operation is similar to gas metal-arc welding, shown in Fig. 30.10.

flux (hence the term *flux-cored*). Cored electrodes produce a more stable arc, improve weld contour, and produce better mechanical properties of the weld metal. The flux in these electrodes is much more flexible than the brittle coating used on SMAW electrodes, so the tubular electrode can be provided in long coiled lengths.

The electrodes are usually 0.5 to 4 mm (0.020 to 0.15 in.) in diameter, and the power required is about 20 kW. Self-shielded cored electrodes also are available. They do not require any external shielding gas, because they contain emissive fluxes that shield the weld area against the surrounding atmosphere. Small-diameter electrodes have made the welding of thinner materials not only possible, but often preferable. Also, small-diameter electrodes make it relatively easy to weld parts in different positions, and the flux chemistry permits the welding of many metals.

The FCAW process combines the versatility of SMAW with the continuous and automatic electrode-feeding feature of GMAW. The process is economical and versatile, so it is used for welding a variety of joints, mainly on steels, stainless steels, and nickel alloys. The higher weld-metal deposition rate of the FCAW process (compared with that of GMAW) has led to its use in the joining of sections of all thicknesses. The use of *tubular electrodes* with very small diameters has extended the use of this process to workpieces of smaller section size.

A major advantage of FCAW is the ease with which specific weld-metal chemistries can be developed. By adding alloying elements to the flux core, virtually any alloy composition can be produced. The process is easy to automate and is readily adaptable to flexible manufacturing systems and robotics.

30.4.5 Electrogas Welding

Electrogas welding (EGW) is used primarily for welding the edges of sections vertically and in one pass with the pieces placed edge to edge (butt joint). It is classified as a *machine-welding process*, because it requires special equipment (Fig. 30.12). The weld metal is deposited into a weld cavity between the two pieces to be joined. The space is enclosed by two water-cooled copper *dams* (*shoes*) to prevent the molten slag from running off; mechanical drives move the shoes upward. Circumferential welds (such as those on pipes) also are possible, with the workpiece rotating.

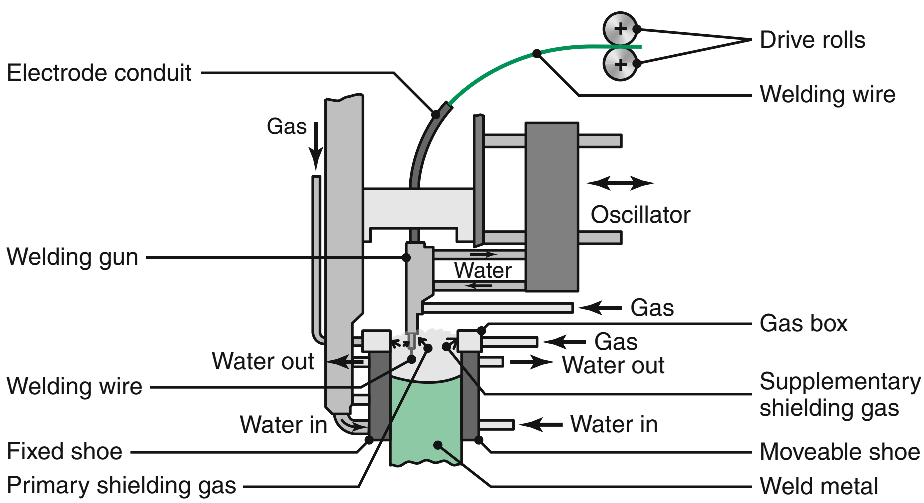


FIGURE 30.12 Schematic illustration of the electrogas-welding process.

Single or multiple electrodes are fed through a conduit, and a continuous arc is maintained by flux-cored electrodes at up to 750 A or solid electrodes at 400 A. Power requirements are about 20 kW. Shielding is done by means of an inert gas, such as carbon dioxide, argon, or helium—depending on the type of material being welded. The gas may be provided either from an external source, from a flux-cored electrode, or from both.

The equipment for electrogas welding is reliable and training for operators is relatively simple. Weld thickness ranges from 12 to 75 mm (0.5 to 3 in.) on steels, titanium, and aluminum alloys. Typical applications are in the construction of bridges, pressure vessels, thick-walled and large-diameter pipes, storage tanks, and ships.

30.4.6 Electroslag Welding

Electroslag welding (ESW) and its applications are similar to electrogas welding (Fig. 30.13). The main difference is that the arc is started between the electrode tip and the bottom of the part to be welded. Flux is added, which then melts by the heat of the arc. After the molten slag reaches the tip of the electrode, the arc is extinguished. Heat is produced continuously by the electrical resistance of the molten slag. Because the arc is extinguished, ESW is not strictly an arc-welding process. Single or multiple solid as well as flux-cored electrodes may be used. The guide may be nonconsumable (conventional method) or consumable.

Electroslag welding is capable of welding plates with thicknesses ranging from 50 mm to more than 900 mm (2 to 36 in.), and welding is done in one pass. The current required is about 600 A at 40 to 50 V, although higher currents are used for thick plates. The travel speed of the weld is in the range from 12 to 36 mm/min (0.5 to 1.5 in./min). Weld quality is good. This process is used for large structural-steel sections, such as heavy machinery, bridges, oil rigs, ships, and nuclear-reactor vessels.

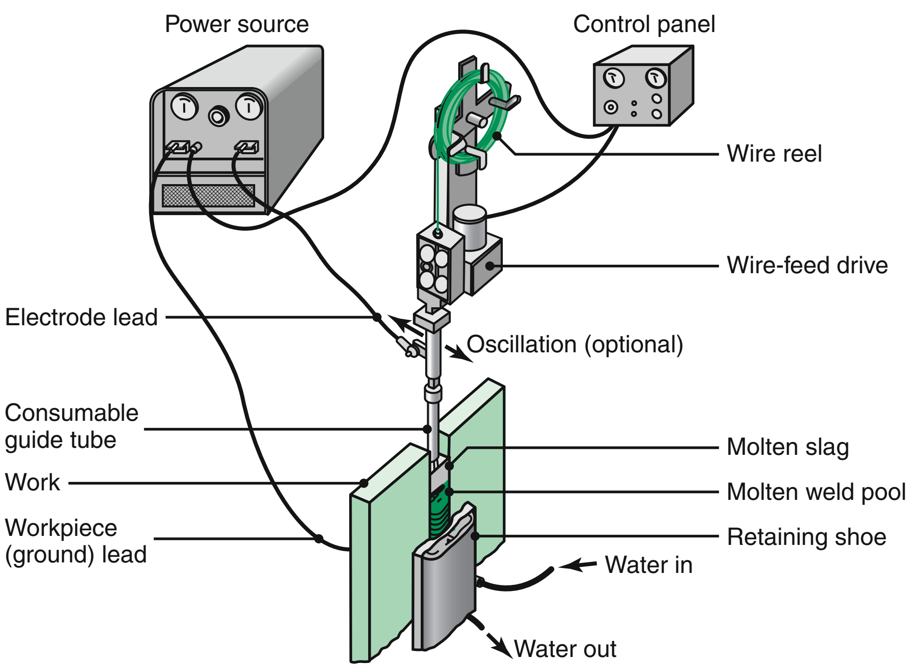


FIGURE 30.13 Equipment used for electroslag-welding operations.

30.5 Electrodes for Arc Welding

Electrodes for consumable arc-welding processes are classified according to the following properties:

- Strength of the deposited weld metal
- Current (AC or DC)
- Type of coating.

Electrodes are identified by numbers and letters (Table 30.3)—or by color code if the numbers and letters are too small to imprint. Typical coated-electrode dimensions are in the range from 150 to 460 mm (6 to 18 in.) in length and 1.5 to 8 mm ($\frac{1}{16}$ to $\frac{5}{16}$ in.) in diameter.

Specifications for electrodes and filler metals (including dimensional tolerances, quality control procedures, and processes) are published by the American Welding Society (AWS) and the American National Standards Institute (ANSI). Some specifications appear in the Aerospace Materials Specifications (AMS) by the Society of Automotive Engineers (SAE). Electrodes are sold by weight and are available in a wide variety of sizes and specifications. Criteria for selection and recommendations for electrodes for a particular metal and its application can be found in supplier literature and in the various handbooks and references listed at the end of this chapter.

TABLE 30.3

Designations for Mild-steel Coated Electrodes

The prefix "E" designates arc welding electrode.
The first two digits of four-digit numbers and the first three digits of five-digit numbers indicate *minimum tensile strength*:

E60XX	60,000 psi
E70XX	70,000
E110XX	110,000

The next-to-last digit indicates position:

EXX1X	All positions
EXX2X	Flat position and horizontal fillets

The last two digits together indicate the type of covering and the current to be used.
The suffix (Example: EXXXX-A1) indicates the approximate alloy in the weld deposit:

—A1	0.5% Mo
—B1	0.5% Cr, 0.5% Mo
—B2	1.25% Cr, 0.5% Mo
—B3	2.25% Cr, 1% Mo
—B4	2% Cr, 0.5% Mo
—B5	0.5% Cr, 1% Mo
—C1	2.5% Ni
—C2	3.25% Ni
—C3	1% Ni, 0.35% Mo, 0.15% Cr
—D1 and D2	0.25–0.45% Mo, 1.75% Mn
—G	0.5% min. Ni, 0.3% min. Cr, 0.2% min. Mo, 0.1% min. V, 1% min. Mn (only one element required)

Electrode Coatings. Electrodes are *coated* with claylike materials that include silicate binders and powdered materials, such as oxides, carbonates, fluorides, metal alloys, cotton cellulose, and wood flour. The coating, which is brittle and takes part in complex interactions during welding, has the following basic functions:

- Stabilize the arc
- Generate gases to act as a shield against the surrounding atmosphere; the gases produced are carbon dioxide, water vapor, and small amounts of carbon monoxide and hydrogen
- Control the rate at which the electrode melts
- Act as a flux to protect the weld against the formation of oxides, nitrides, and other inclusions and, with the resulting slag, to protect the molten-weld pool
- Add alloying elements to the weld zone to enhance the properties of the joint—among these elements are deoxidizers to prevent the weld from becoming brittle.

The deposited electrode coating or slag must be removed after each pass in order to ensure a good weld; a wire brush (manual or power) can be used for this purpose. Bare electrodes and wires made of stainless steels and aluminum alloys also are available. They are used as filler metals in various welding operations.

30.6 Electron-beam Welding

In *electron-beam welding* (EBW), developed in the 1960s, heat is generated by high-velocity narrow-beam electrons. The kinetic energy of the electrons is converted into heat as they strike the workpiece. The process requires special equipment to focus the beam on the workpiece, typically in a vacuum. The higher the vacuum, the more the beam penetrates, and the greater is the depth-to-width ratio; thus, the methods are called EBW-HV (for "high vacuum") and EBW-MV (for "medium vacuum"); some materials also may also be welded by EBW-NV (for "no vacuum").

Almost any metal can be welded by EBW, and workpiece thicknesses can range from foil to plate. Capacities of electron guns range up to 100 kW. The intense energy also is capable of producing holes in the workpiece (see **keyhole technique**, Section 30.3). Generally, no shielding gas, flux, or filler metal is required.

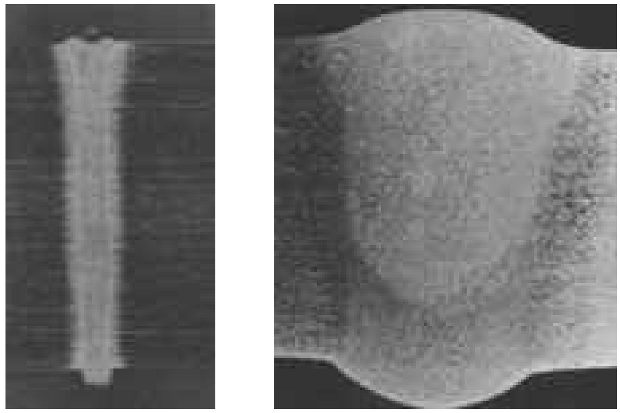
The EBW process has the capability of making high-quality welds that are almost parallel sided, are deep and narrow, and have small heat-affected zones (see Section 30.9). Depth-to-width ratios range between 10 and 30. The sizes of welds made by EBW are much smaller than those of welds made by conventional processes. With the use of automation and servo controls, parameters can be controlled accurately at welding speeds as high as 12 m/min (40 ft/min).

Almost any metal can be butt or lap welded with this process at thicknesses up to 150 mm (6 in.). Distortion and shrinkage in the weld area are minimal. The weld quality is good and of very high purity. Typical applications include the welding of aircraft, missile, nuclear, and electronic components, as well as gears and shafts for the automotive industry. Electron-beam welding equipment generates X-rays; hence, proper monitoring and periodic maintenance are essential.

30.7 Laser-beam Welding

Laser-beam welding (LBW) utilizes a high-power laser beam as the source of heat, to produce a fusion weld. Because the beam can be focused onto a very small area, it has high energy density and deep-penetrating capability. The beam can be directed, shaped, and focused precisely on the workpiece. Consequently, this process is suitable particularly for welding deep and narrow joints (Fig. 30.14) with depth-to-width ratios typically ranging from 4 to 10.

Laser-beam welding has become extremely popular and is used in most industries. In the automotive industry, welding transmission components are the most widespread application. Among numerous other applications is the welding of thin parts for electronic components. The laser beam may be **pulsed** (in milliseconds) with power levels up to 100 kW for applications such as the spot welding of thin materials. **Continuous** multi-kW laser systems are used for deep welds on thick sections.



(a) (b)

FIGURE 30.14 Comparison of the sizes of weld beads: (a) laser-beam or electron-beam welding and (b) tungsten-arc welding. *Source*: Courtesy of American Welding Society.

Laser-beam welding produces welds of good quality with minimum shrinkage or distortion. Laser welds have good strength and generally are ductile and free of porosity. The process can be automated to be used on a variety of materials with thicknesses up to 25 mm (1 in.); it is particularly effective on thin workpieces. As described in Section 16.2.2, *tailor-welded* sheet-metal blanks are joined principally by laser-beam welding using robotics for precise control of the beam path.

Typical metals and alloys welded include aluminum, titanium, ferrous metals, copper, superalloys, and the refractory metals. Welding speeds range from 2.5 m/min (8 ft/min) to as high as 80 m/min (250 ft/min) for thin metals. Because of the nature of the process, welding can be done in otherwise inaccessible locations. As in other and similar automated welding systems, the operator skill required is minimal. Safety is particularly important in laser-beam welding due to the extreme hazards to the eye as well as the skin; solid-state (YAG) lasers also are dangerous. (See Table 27.2 on types of lasers.)

The major advantages of LBW over EBW are the following:

- A vacuum is not required, and the beam can be transmitted through air
- Laser beams can be shaped, manipulated, and focused optically (by means of fiber optics), so the process can be automated easily
- The beams do not generate X-rays
- The quality of the weld is better than in EBW; the weld has less tendency toward incomplete fusion, spatter, and porosity; and there is less distortion.

EXAMPLE 30.2 Laser Welding of Razor Blades

A close-up of the Gillette Sensor™ razor cartridge is shown in Fig. 30.15. Each of the two narrow, high-strength blades has 13 pinpoint welds—11 of which can be seen (as darker spots, about 0.5 mm in diameter) on each blade in the photograph. You can inspect the welds on actual blades with a magnifying glass or a microscope.

The welds are made with an Nd:YAG laser equipped with fiber-optic delivery. This equipment provides very flexible beam manipulation and can target exact locations along the length of the blade. With a set of these machines, production is at a rate of 3 million welds per hour, with accurate and consistent weld quality.

Source: Courtesy of Lumonics Corporation, Industrial Products Division.

FIGURE 30.15 Detail of Gillette Sensor™ razor cartridge, showing laser spot welds.

30.8 Cutting

In addition to being cut by mechanical means, material can be cut into various contours with the use of a heat source that melts and removes a narrow zone in the workpiece. The sources of heat can be torches, electric arcs, or lasers.

Oxyfuel–gas Cutting. *Oxyfuel–gas cutting* (OFC) is similar to oxyfuel welding, but the heat source is now used to remove a narrow zone from a metal plate or sheet (Fig. 30.16a). This process is suitable particularly for steels. The basic reactions with steel are

$$\mathrm{Fe} + \mathrm{O} \longrightarrow \mathrm{FeO} + \mathrm{Heat}, \tag{30.6}$$

$$3\mathrm{Fe} + 2\mathrm{O}_2 \longrightarrow \mathrm{Fe}_3\mathrm{O}_4 + \mathrm{Heat}, \tag{30.7}$$

and

$$4\mathrm{Fe} + 3\mathrm{O}_2 \longrightarrow 2\ \mathrm{Fe}_2\mathrm{O}_3 + \mathrm{Heat}. \tag{30.8}$$

The greatest heat is generated by the second reaction, and it can produce a temperature rise to about 870°C (1600°F). However, this temperature is not sufficiently high to cut steels; therefore, the workpiece is *preheated* with fuel gas, and oxygen is introduced later (see the nozzle cross section in Fig. 30.16a). The higher the carbon content of the steel, the higher is the preheating temperature required. Cutting takes place mainly by the oxidation (burning) of the steel; some melting also takes place. Cast irons and steel castings also can be cut by this method. The process generates a **kerf** similar to that produced by sawing with a saw blade or by wire electrical-discharge machining (see Fig. 27.12).

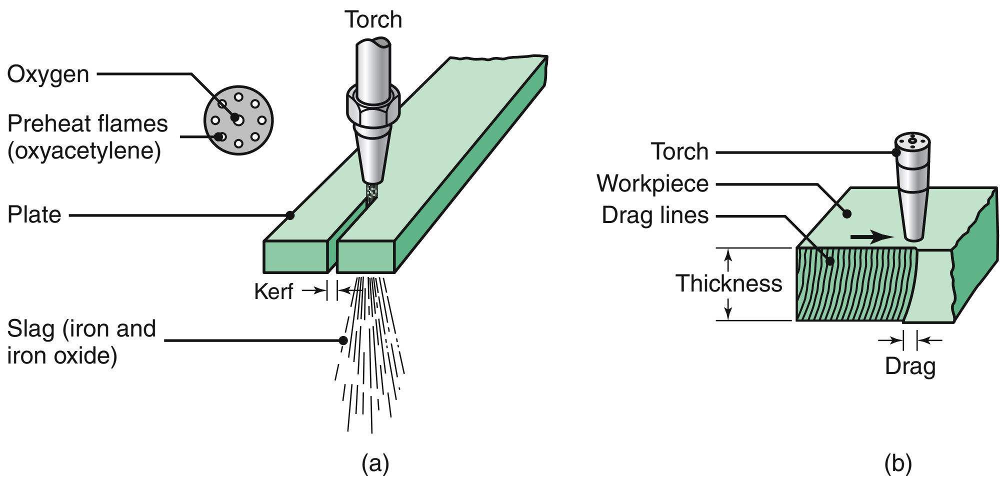


FIGURE 30.16 (a) Flame cutting of a steel plate with an oxyacetylene torch, and a cross section of the torch nozzle. (b) Cross section of a flame-cut plate, showing drag lines.

The maximum thickness that can be cut by OFC depends mainly on the gases used. With oxyacetylene gas, the maximum thickness is about 300 mm (12 in.); with oxyhydrogen, it is about 600 mm (24 in.). Kerf widths range from about 1.5 to 10 mm (0.06 to 0.4 in.), with reasonably good control of tolerances. The flame leaves **drag lines** on the cut surface (Fig. 30.16b), resulting in a rougher surface than that produced by processes such as sawing, blanking, or other operations that use mechanical cutting tools. Distortion caused by uneven temperature distribution can be a problem in OFC.

Although long used for salvage and repair work, OFC can be used in manufacturing as well. Torches may be guided along specified paths either manually, mechanically, or automatically by machines using programmable controllers and robots. *Underwater cutting* is done with specially designed torches that produce a blanket of compressed air between the flame and the surrounding water.

Arc Cutting. *Arc-cutting* processes are based on the same principles as arc-welding processes. A variety of materials can be cut at high speeds by arc cutting. As in welding, these processes also leave a heat-affected zone that needs to be taken into account, particularly in critical applications.

In **air carbon-arc cutting** (CAC-A), a carbon electrode is used and the molten metal is blown away by a high-velocity air jet; thus, the metal being cut doesn't have to oxidize. This process is used especially for gouging and scarfing (removal of metal from a surface). However, the process is noisy, and the molten metal can be blown substantial distances and cause safety hazards.

Plasma-arc cutting (PAC) produces the highest temperatures. It is used for the rapid cutting of nonferrous and stainless-steel plates. The cutting productivity of this process is higher than that of oxyfuel–gas methods. PAC produces a good surface finish and narrow kerfs, and is the most popular cutting process utilizing programmable controllers employed in manufacturing today.

Electron beams and **lasers** also are used for very accurately cutting a wide variety of metals, as was described in Sections 27.6 and 27.7. The surface finish is better than that of other thermal cutting processes, and the kerf is narrower.

30.9 The Weld Joint, Quality, and Testing

Three distinct zones can be identified in a typical weld joint, as shown in Fig. 30.17:

1. **Base metal**
2. **Heat-affected zone**
3. **Weld metal.**

The metallurgy and properties of the second and third zones depend strongly on the type of metals joined, the particular joining process, the filler metals used (if any), and welding process variables. A joint produced without a filler metal is called *autogenous*, and its weld zone is composed of the *resolidified base metal*. A joint made with a filler metal has a central zone called the *weld metal* and is composed of a mixture of the base and the filler metals.

Solidification of the Weld Metal. After the application of heat and the introduction of the filler metal (if any) into the weld zone, the weld joint is allowed to cool to ambient temperature. The *solidification* process is similar to that in casting and begins with the formation of columnar (dendritic) grains. (See Fig. 10.3.) These grains are relatively long and form parallel to the heat flow. Because metals are much better heat conductors than the surrounding air, the grains lie parallel to the plane of the two components being welded (Fig. 30.18a). In contrast, the grains in a shallow weld are shown in Fig. 30.18b and c.

Grain structure and grain size depend on the specific metal alloy, the particular welding process employed, and the type of filler metal. Because it began in a molten state, the weld metal basically has a *cast structure*, and since it has cooled slowly, it has coarse grains. Consequently, this structure generally has low strength, toughness, and ductility. However, the proper selection of filler-metal composition or of heat treatments following welding can improve the mechanical properties of the joint.

The resulting structure depends on the particular alloy, its composition, and the thermal cycling to which the joint is subjected. For example, cooling rates may be controlled and reduced by *preheating* the general weld area prior to welding. Preheating is important, particularly for metals having high thermal conductivity, such as aluminum and copper. Without preheating, the heat produced during welding dissipates rapidly through the rest of the parts being joined.

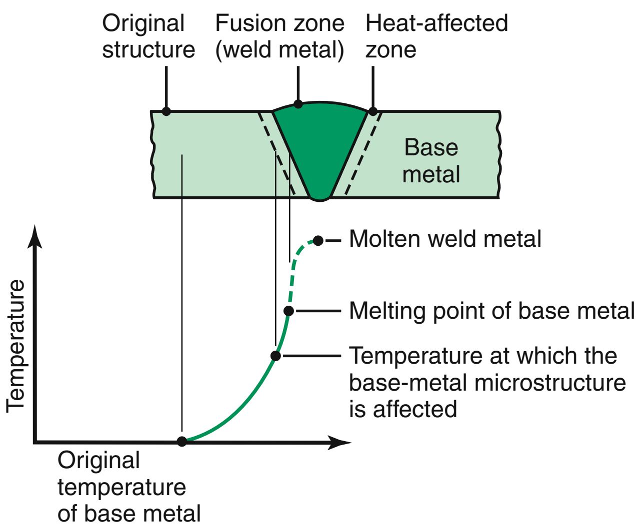


FIGURE 30.17 Characteristics of a typical fusion-weld zone in oxyfuel–gas and arc welding.

Heat-affected Zone. The *heat-affected zone* (HAZ) is within the base metal itself. It has a microstructure different from that of the base metal prior to welding, because it has been temporarily subjected to elevated temperatures during welding. The portions of the base metal that are far enough away from the heat source do not undergo any microstructural changes during welding because of the far lower temperature to which they are subjected.

The properties and microstructure of the HAZ depend on (a) the rate of heat input and cooling and (b) the temperature to which this zone was raised. In addition to metallurgical factors (such as the original grain size, grain orientation, and degree of prior cold

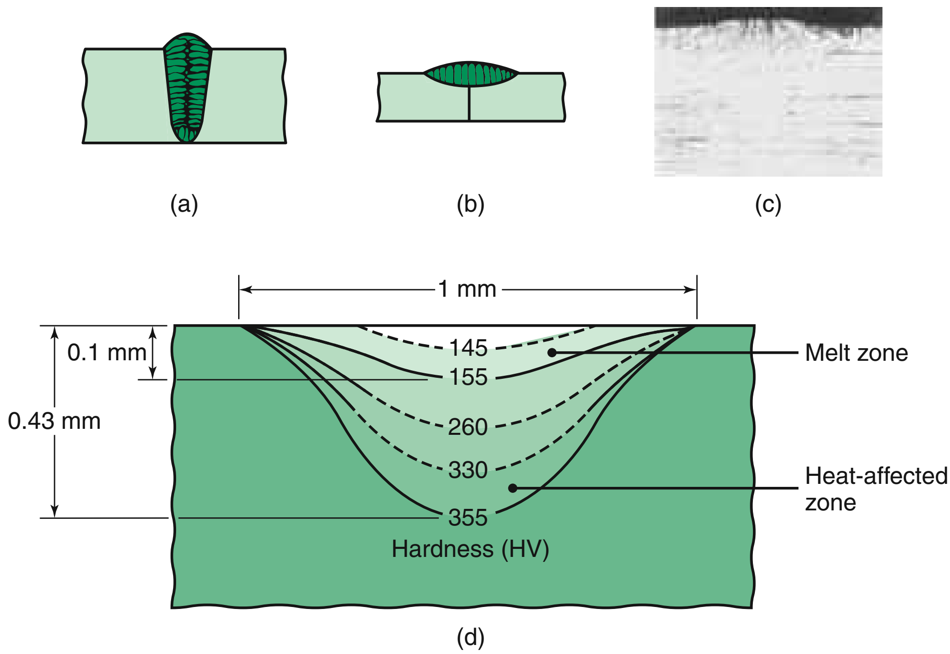


FIGURE 30.18 Grain structure in (a) a deep weld and (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal. (c) Weld bead on a cold-rolled nickel strip produced by a laser beam. (d) Microhardness (HV) profile across a weld bead.

work), physical properties (such as the specific heat and thermal conductivity of the metals) influence the size and characteristics of the HAZ.

The strength and hardness of the HAZ (Fig. 30.18d) depend partly on how the original strength and hardness of the base metal was developed prior to the welding. As was described in Chapters 2 and 4, they may have been developed by (a) cold working, (b) solid-solution strengthening, (c) precipitation hardening, or (d) various heat treatments. The effects of these strengthening methods are complex, and the simplest to analyze are those in a base metal that has been cold worked, such as by cold rolling or cold forging.

The heat applied during welding *recrystallizes* the elongated grains of the cold-worked base metal. On the one hand, grains that are away from the weld metal will recrystallize into fine, equiaxed grains. On the other hand, grains close to the weld metal have been subjected to elevated temperatures for a longer time. Consequently, the grains will grow in size (grain growth), and this region will be softer and have lower strength. Such a joint will be weakest at its HAZ.

The effects of heat on the HAZ for joints made from dissimilar metals and for alloys strengthened by other methods are so complex as to be beyond the scope of this book. Details can be found in the more advanced references listed in the bibliography at the end of this chapter.

30.9.1 Weld Quality

As a result of a history of thermal cycling and its attendant microstructural changes, a welded joint may develop various **discontinuities**. Welding discontinuities also can be caused by an inadequate or careless application of proper welding technologies or by poor operator training. The major discontinuities that affect weld quality are described here.

Porosity. *Porosity* in welds may be caused by

- Gases released during melting of the weld area, but trapped during solidification
- Chemical reactions during welding
- Contaminants.

Most welded joints contain some porosity, which is generally in the shape of spheres or of elongated pockets. (See also Section 10.6.1.) The distribution of porosity in the weld zone may be random, or the porosity may be concentrated in a certain region in the zone.

Porosity in welds can be reduced by the following practices:

- Proper selection of electrodes and filler metals
- Improved welding techniques, such as preheating the weld area or increasing the rate of heat input
- Proper cleaning and the prevention of contaminants from entering the weld zone
- Reduced welding speeds to allow time for gas to escape.

Slag Inclusions. *Slag inclusions* are compounds such as oxides, fluxes, and electrode-coating materials that are trapped in the weld zone. If shielding gases are not effective during welding, contamination from the environment also may contribute to such inclusions. Welding conditions are important as well: With control of welding process parameters, the molten slag will float to the surface of the molten weld metal and thus will not become entrapped.

Slag inclusions can be prevented by the following practices:

- Cleaning the weld-bead surface by means of a wire brush (hand or power) or a chipper before the next layer is deposited
- Providing sufficient shielding gas
- Redesigning the joint to permit sufficient space for proper manipulation of the puddle of molten weld metal.

Incomplete Fusion and Penetration. *Incomplete fusion* produces poor weld beads, such as those shown in Fig. 30.19. A better weld can be obtained by the use of the following practices:

- Raising the temperature of the base metal
- Cleaning the weld area before welding

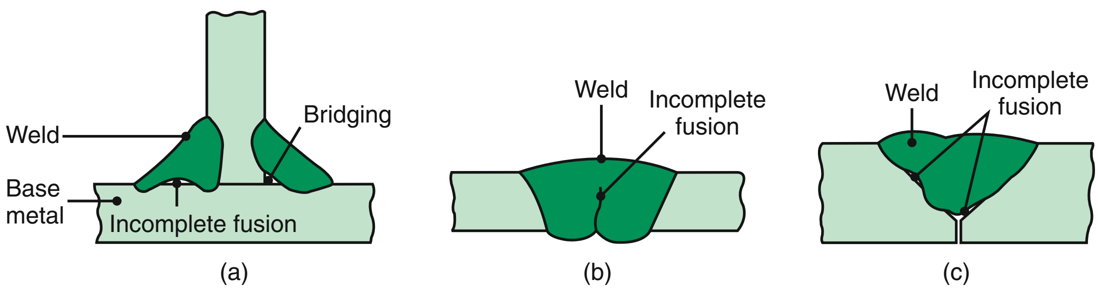


FIGURE 30.19 Examples of various discontinuities in fusion welds.

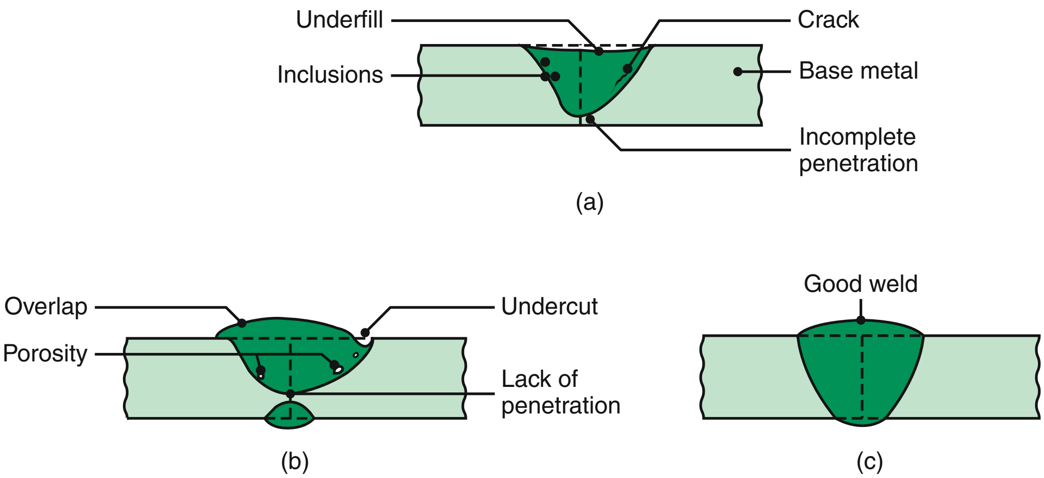


FIGURE 30.20 Examples of various defects in fusion welds.

- Modifying the joint design and changing the type of electrode used
- Providing sufficient shielding gas.

Incomplete penetration occurs when the depth of the welded joint is insufficient. Penetration can be improved by the following practices:

- Increasing the heat input
- Reducing the travel speed during the welding
- Modifying the joint design
- Ensuring that the surfaces to be joined fit each other properly.

Weld Profile. *Weld profile* is important not only because of its effects on the strength and appearance of the weld, but also because it can indicate incomplete fusion or the presence of slag inclusions in multiple-layer welds.

- **Underfilling** results when the joint is not filled with the proper amount of weld metal (Fig. 30.20a).
- **Undercutting** results from the melting away of the base metal and the consequent generation of a groove in the shape of a sharp recess or notch (Fig. 30.20b). If it is deep or sharp, an undercut can act as a stress raiser and can reduce the fatigue strength of the joint; in such cases, it may lead to premature failure.
- **Overlap** is a surface discontinuity (Fig. 30.20b) usually caused by poor welding practice or by the selection of improper materials. A good weld is shown in Fig. 30.20c.

Cracks. Cracks may occur in various locations and directions in the weld area. Typical types of cracks are longitudinal, transverse, crater, underbead, and toe cracks (Fig. 30.21).

Cracks generally result from a combination of the following factors:

- Temperature gradients that cause thermal stresses in the weld zone
- Variations in the composition of the weld zone that cause different rates of contraction during cooling
- Embrittlement of grain boundaries (Section 1.5.2), caused by the segregation of such elements as sulfur to the grain boundaries and occurring when the solid–liquid boundary moves when the weld metal begins to solidify

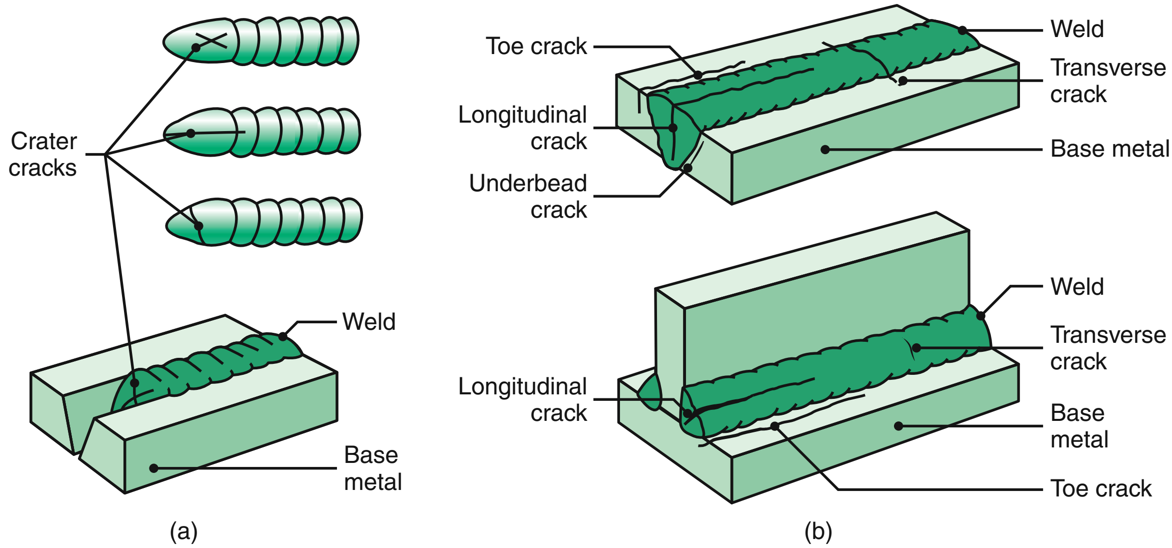


FIGURE 30.21 Types of cracks developed in welded joints. The cracks are caused by thermal stresses, similar to the development of hot tears in castings, as shown in Fig. 10.12.

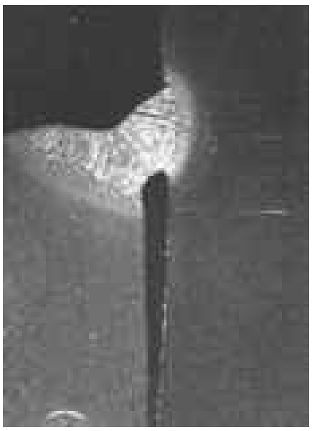


FIGURE 30.22 Crack in a weld bead. The two welded components were not allowed to contract freely after the weld was completed. *Source*: Courtesy of Packer Engineering.

- Hydrogen embrittlement (Section 2.10.2)
- Inability of the weld metal to contract during cooling (Fig. 30.22). This is a situation similar to *hot tears* that develop in castings (Fig 10.12) and is related to excessive restraint of the workpiece during the welding operation.

Cracks also are classified as **hot cracks**, which occur while the joint is still at elevated temperatures, and **cold cracks**, which develop after the weld metal has solidified.

The basic crack-prevention measures in welding are the following:

- Modify the joint design to minimize stresses developed from shrinkage during cooling
- Change the parameters, procedures, and sequence of the welding operation
- Preheat the components to be welded
- Avoid rapid cooling of the welded components.

Lamellar Tears. In describing the anisotropy of plastically deformed metals in Section 1.5, it was stated that the workpiece is weaker when tested in its thickness direction because of the alignment of nonmetallic impurities and inclusions (stringers). This condition is particularly evident in rolled plates and in structural shapes. In welding such components, *lamellar tears* may develop because of shrinkage of the restrained components of the structure during cooling. Such tears can be avoided by providing for shrinkage of the members or by modifying the joint design to make the weld bead penetrate the weaker component more deeply.

Surface Damage. Some of the metal may spatter during welding and be deposited as small droplets on adjacent surfaces. In arc-welding processes, the electrode inadvertently may touch the parts being welded at places other than the weld zone. (Such encounters are called **arc strikes.**) The surface discontinuities thereby produced may be objectionable for reasons of appearance or of subsequent use of the welded part. If severe, these discontinuities adversely may affect the properties of the welded structure, particularly for notch-sensitive metals. Using proper welding techniques and procedures is important in avoiding surface damage.

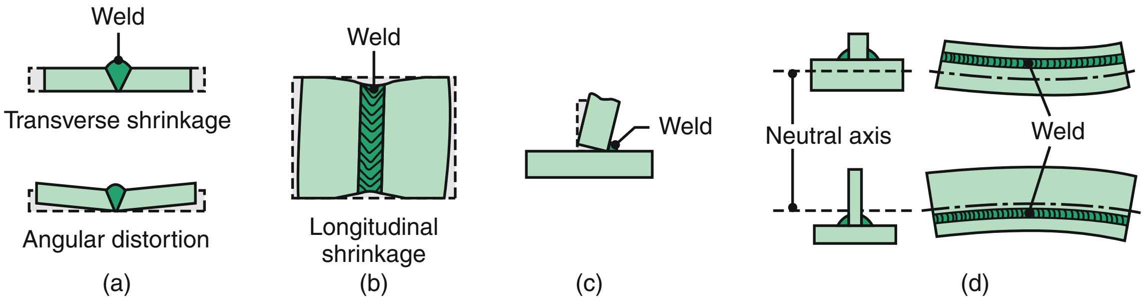


FIGURE 30.23 Distortion of parts after welding. Distortion is caused by differential thermal expansion and contraction of different regions of the welded assembly.

Residual Stresses. Because of localized heating and cooling during welding, the expansion and contraction of the weld area causes *residual stresses* in the workpiece. (See also Section 2.11.) Residual stresses can lead to the following defects:

- Distortion, warping, and buckling of the welded parts (Fig. 30.23)
- Stress-corrosion cracking (Section 2.10.2)
- Further distortion if a portion of the welded structure is subsequently removed, such as by machining or sawing
- Reduced fatigue life of the welded structure.

The type and distribution of residual stresses in welds is described best by reference to Fig. 30.24a. When two plates are being welded, a long, narrow zone is subjected to elevated temperatures, while the plates, as a whole, are essentially at ambient temperature. After the weld is completed and as time elapses, the heat from the weld zone dissipates laterally into the plates, while the weld area cools. Thus, the plates begin to expand longitudinally, while the welded length begins to contract (Fig. 30.23).

If the plate is not constrained, it will warp, as shown in Fig. 30.23a. However, if the plate is not free to warp, it will develop residual stresses that typically are distributed throughout the material, such as the stresses shown in Fig. 30.24. Note that the magnitude of the compressive residual stresses in the plates diminishes to zero at a point far away from the weld area. Because no external forces are acting on the welded plates, the tensile and compressive forces represented by these residual stresses must balance each other.

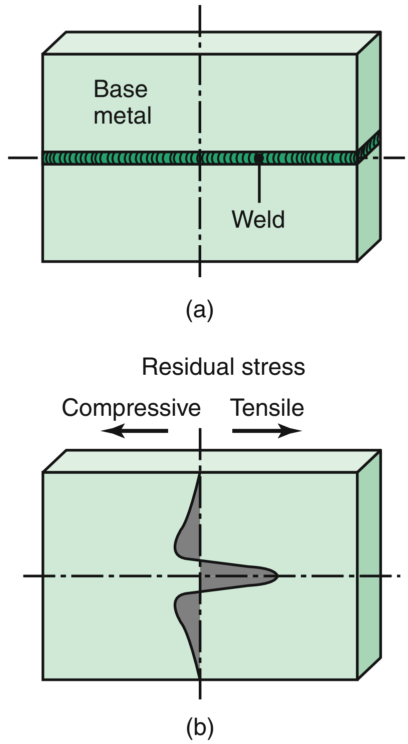


FIGURE 30.24 Residual stresses developed in (a) a straight-butt joint. Note that the residual stresses shown in (b) must be balanced internally. (See also Fig. 2.29.)

Events leading to the distortion of a welded structure are shown in Fig. 30.25. Before welding, the structure is stress free, as shown in Fig. 30.25a. The shape may be fairly rigid, and fixturing also may be present to support the structure. When the weld bead is placed, the molten metal fills the gap between the surfaces to be joined, and flows outward to form the weld bead. At this point, the weld is not under any stress. Afterward, the weld bead solidifies, and both the weld bead and the surrounding material cool to room temperature. As these materials cool, they tend to contract, but are constrained by the bulk of the weldment. The result is that the weldment distorts (Fig. 30.25c) and residual stresses develop.

The residual-stress distribution shown in Fig. 30.25 places the weld and the HAZ in a state of residual tension, which is harmful from a fatigue standpoint.

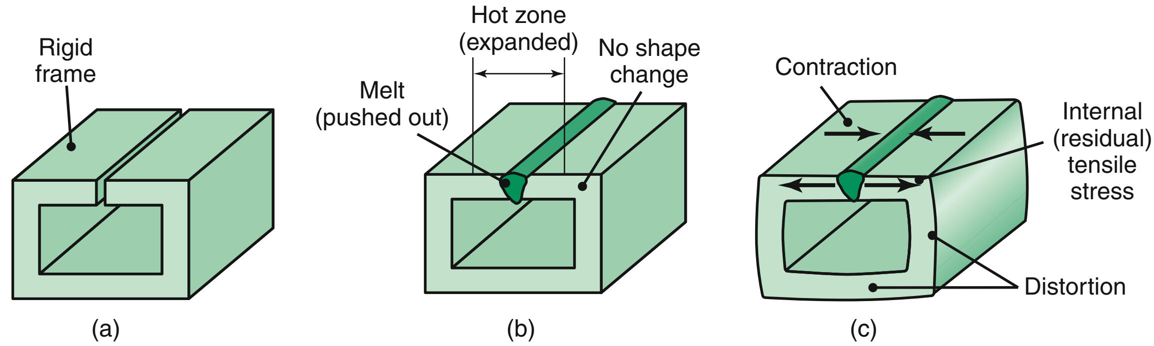


FIGURE 30.25 Distortion of a welded structure. *Source*: After J.A. Schey.

Many welded structures will use cold-worked materials (such as extruded or roll-formed shapes), and these are relatively strong and fatigue resistant. The weld itself may have porosity (see Fig. 30.20b), which can act as a stress riser and aid fatigue-crack growth, or there could be other cracks that can grow in fatigue. In general, the HAZ is less fatigue resistant than the base metal. Thus, the residual stresses developed can be very harmful, and it is not unusual to further treat welds in highly stressed or fatigue-susceptible applications.

In complex welded structures, residual-stress distributions are three dimensional and, consequently, difficult to analyze. The previous discussion involved two plates that were not restrained from movement. In other words, the plates were not an integral part of a larger structure. If, however, they are restrained, reaction stresses will be generated, because the plates are not free to expand or contract. This situation arises particularly in structures with high stiffness.

Stress Relieving of Welds. The problems caused by residual stresses (such as distortion, buckling, and cracking) can be reduced by **preheating** the base metal or the parts to be welded. Preheating reduces distortion by reducing the cooling rate and the level of thermal stresses developed (by lowering the elastic modulus). This technique also reduces shrinkage and possible cracking of the joint.

For optimum results, preheating temperatures and cooling rates must be controlled carefully in order to maintain acceptable strength and toughness in the welded structure. The workpieces may be heated in several ways, including (a) in a furnace, (b) electrically (resistively or inductively), or (c) by radiant lamps or a hot-air blast for thin sections. The temperature and time required for *stress relieving* depend on the type of material and on the magnitude of the residual stresses developed.

Other methods of stress relieving include peening, hammering, or surface rolling of the weld-bead area. These techniques induce compressive residual stresses, which, in turn, lower or eliminate tensile residual stresses in the weld. For multilayer welds, the first and last layers should not be peened, in order to protect them against possible peening damage.

Residual stresses can also be relieved or reduced by plastically deforming the structure by a small amount. For instance, this technique can be used in welded pressure vessels by pressurizing the vessels internally (*proof stressing*). In order to reduce the possibility of sudden fracture under high internal pressure, the weld must be made properly and must be free of notches and discontinuities, which could act as points of stress concentration.

In addition to being preheated for stress relieving, welds may be *heat treated* by various other techniques in order to modify other properties. These techniques include the annealing, normalizing, quenching, and tempering of steels and the solution treatment and aging of various alloys as described in Chapter 4.

30.9.2 Weldability

The *weldability* of a metal is usually defined as its capacity to be welded into a specific structure that has certain properties and characteristics and will satisfactorily meet service requirements. Weldability involves a large number of variables; hence, generalizations are difficult. As noted previously, the material characteristics (such as alloying elements, impurities, inclusions, grain structure, and processing history) of both the base metal and the filler metal are important. For example, the weldability of steels decreases with increasing carbon content because of martensite formation (which is hard and brittle) and thus reduces the strength of the weld. Coated steel sheets present various challenges in welding, depending on the type and thickness of the coating.

Because of the effects of melting and solidification and of the associated microstructural changes, a thorough knowledge of the phase diagram and the response of the metal or alloy to sustained elevated temperatures is essential. Also influencing weldability are mechanical and physical properties: strength, toughness, ductility, notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion, surface-tension characteristics of the molten metal, and corrosion resistance.

The preparation of surfaces for welding is important, as are the nature and properties of surface-oxide films and of adsorbed gases. The particular welding process employed significantly affects the temperatures developed and their distribution in the weld zone. Other factors that affect weldability are shielding gases, fluxes, moisture content of the coatings on electrodes, welding speed, welding position, cooling rate, and level of preheating, as well as such postwelding techniques as stress relieving and heat treating.

Weldability of Ferrous Materials:

- *Plain-carbon steels:* Weldability is excellent for low-carbon steels, fair to good for medium-carbon steels, poor for high-carbon steels.
- *Low-alloy steels:* Weldability is similar to that of medium-carbon steels.
- *High-alloy steels:* Weldability generally is good under well-controlled conditions.
- *Stainless steels:* These generally are weldable by various processes.
- *Cast irons:* These generally are weldable, although their weldability varies greatly.

Weldability of Nonferrous Materials:

- *Aluminum alloys:* These are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important. Aluminum alloys containing zinc or copper generally are considered unweldable.
- *Copper alloys:* Depending on composition, these generally are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important.
- *Magnesium alloys:* These are weldable with the use of a protective shielding gas and fluxes.
- *Nickel alloys:* Weldability is similar to that of stainless steels. The lack of sulfur is undesirable.
- *Titanium alloys:* These are weldable with the proper use of shielding gases.
- *Tantalum:* Weldability is similar to that of titanium.

- *Tungsten:* Weldable under well-controlled conditions.
- *Molybdenum:* Weldability is similar to that of tungsten.
- *Niobium (columbium):* Possesses good weldability.

30.9.3 Testing of Welds

As in all manufacturing processes, the quality of a welded joint is established by testing. Several standardized tests and test procedures have been established. They are available from many organizations, such as the American Society for Testing and Materials (ASTM), the American Welding Society (AWS), the American Society of Mechanical Engineers (ASME), the American Society of Civil Engineers (ASCE), and various federal agencies.

Welded joints may be tested either *destructively* or *nondestructively*. (See also Sections 36.10 and 36.11.) Each technique has certain capabilities and limitations, as well as sensitivity, reliability, and requirements for special equipment and operator skill.

Destructive Testing Techniques:

- **Tension test:** Longitudinal and transverse tension tests are performed on specimens removed from actual welded joints and from the weld-metal area. Stress–strain curves are then obtained by the procedures described in Section 2.2. These curves indicate the yield strength, *Y*, ultimate tensile strength, UTS, and ductility of the welded joint (elongation and reduction of area) in different locations and directions.
- **Tension-shear test:** The specimens in the tension-shear test (Fig. 30.26a and b) are prepared to simulate conditions to which actual welded joints are subjected. These specimens are subjected to tension so that the shear strength of the weld metal and the location of fracture can be determined.

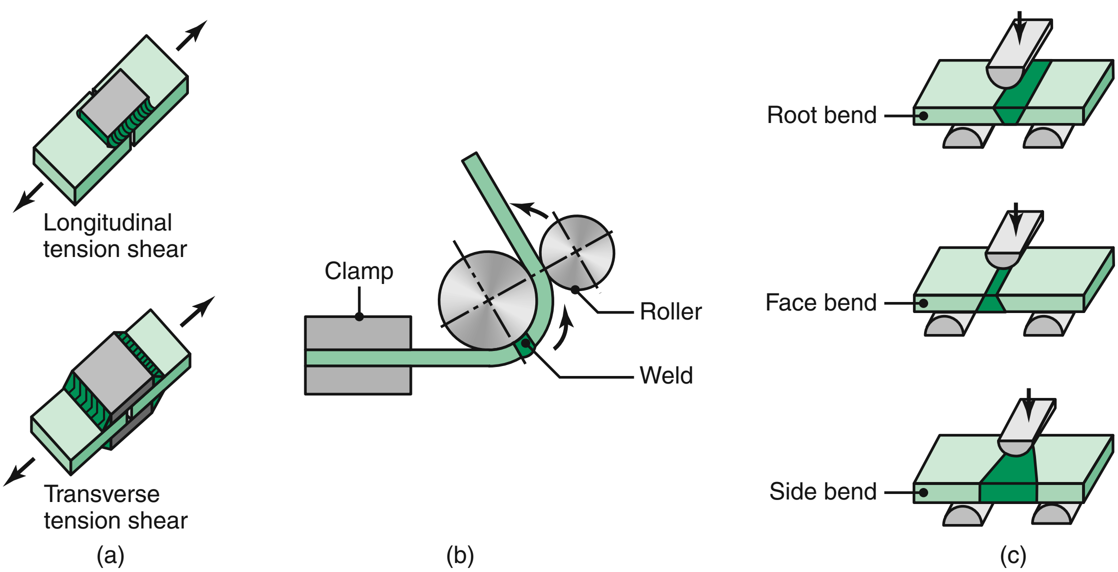


FIGURE 30.26 (a) Specimens for longitudinal tension-shear testing and for transfer tension-shear testing. (b) Wraparound bend-test method. (c) Three-point transverse bending of welded specimens.

- **Bend test:** Several bend tests have been developed to determine the ductility and strength of welded joints. In one common test, the welded specimen is bent around a fixture (*wraparound* bend test, Fig. 30.26c). In another test, the specimens are tested in *three-point transverse bending* (Fig. 30.26d; see also Fig. 2.11a). These tests help to determine the relative ductility and strength of welded joints.
- **Fracture toughness test:** Fracture toughness tests commonly utilize the impact-testing techniques described in Section 2.9. *Charpy V-notch* specimens are first prepared and then tested for toughness. Another toughness test is the *drop-weight test*, in which the energy is supplied by a falling weight.
- **Corrosion and creep tests:** In addition to undergoing mechanical tests, welded joints also may be tested for their resistance to corrosion and creep. Because of the difference in the composition and microstructure of the materials in the weld zone, *preferential corrosion* may take place in the zone. Creep tests are important in determining the behavior of welded joints and structures subjected to elevated temperatures.

Nondestructive Testing Techniques. Welded structures often have to be tested nondestructively, particularly for critical applications in which weld failure can be catastrophic, such as in pressure vessels, load-bearing structural members, and power plants. Nondestructive testing techniques for welded joints generally consist of the following methods (these tests are described in Section 36.10):

- **Visual**
- **Radiographic (X-rays)**
- **Magnetic-particle**
- **Liquid-penetrant**
- **Ultrasonic.**

Testing for hardness distribution in the weld zone also may be a useful indicator of weld strength and microstructural changes.

30.10 Joint Design and Process Selection

In describing individual welding processes, several examples were given concerning the types of welds and joints produced and their applications in numerous consumer and industrial products of various designs. Typical types of joints produced by welding, together with their terminology, are shown in Fig. 30.27. Standardized symbols commonly used in engineering drawings to describe the types of welds are shown in Fig. 30.28. These symbols identify the type of weld, the groove design, the weld size and length, the welding process, the sequence of operations, and other necessary information.

The general design guidelines for welding may be summarized as follows, with some examples given in Fig. 30.29 (various other types of joint design will be given in Chapters 31 and 32):

- Product design should minimize the number of welds because, unless automated, welding can be costly.
- Weld location should be selected so as to avoid excessive stresses or stress concentrations in the welded structure and for appearance.
- Weld location should be selected so as not to interfere with any subsequent processing of the joined components or with their intended use.

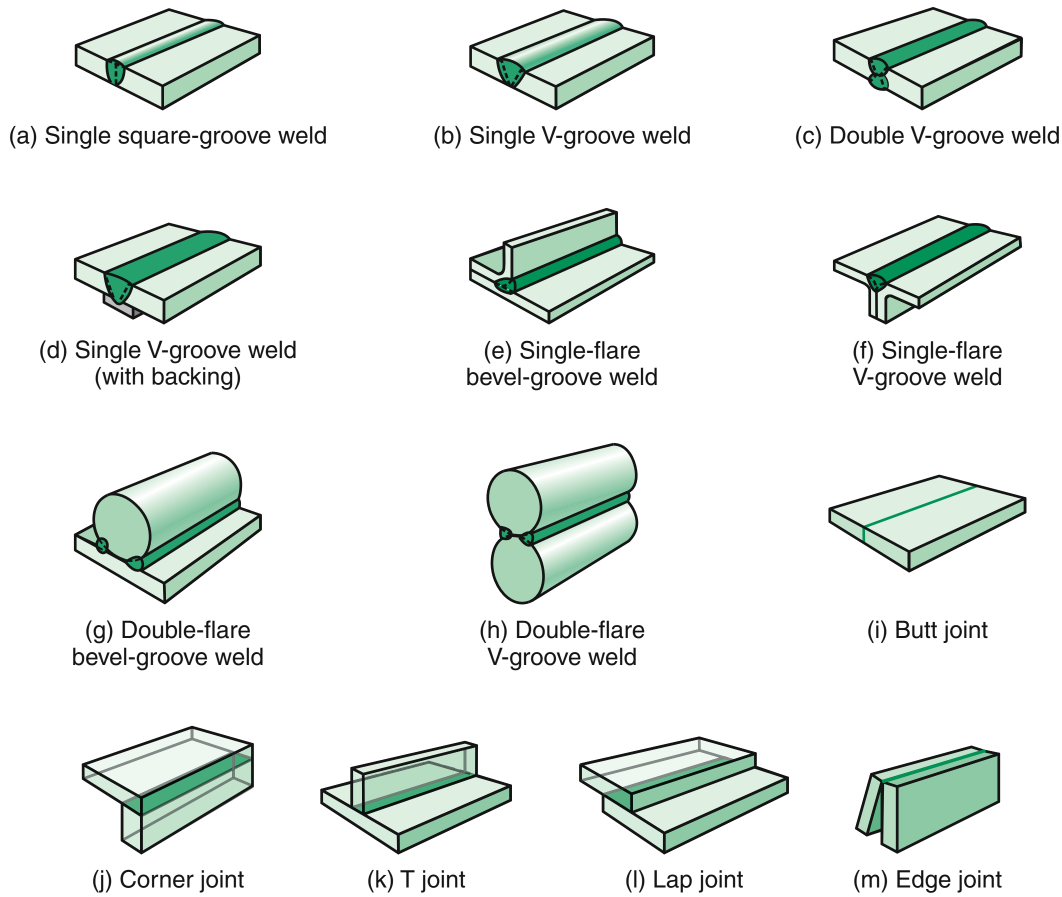


FIGURE 30.27 Examples of welded joints and their terminology.

- Components should fit properly prior to welding. The method used to prepare edges, such as sawing, machining, or shearing, also can affect weld quality.
- The need for edge preparation should be avoided or minimized.
- Weld-bead size should be as small as possible, while maintaining the strength of the joint, to conserve weld metal and for better appearance.

Welding Process Selection. In addition to taking into account the process characteristics, capabilities, and material considerations described thus far in this chapter, the selection of a weld joint and an appropriate welding process involve the following considerations (see also Chapters 31 and 32).

- Configuration of the parts or structure to be joined, joint design, thickness and size of the components, and number of joints required.
- The methods used in manufacturing the components to be joined.
- Types of materials involved, which may be metallic or nonmetallic.
- Location, accessibility, and ease of joining.
- Application and service requirements, such a type of loading, any stresses generated, and the environment.
- Effects of distortion, warping, discoloration of appearance, and service.

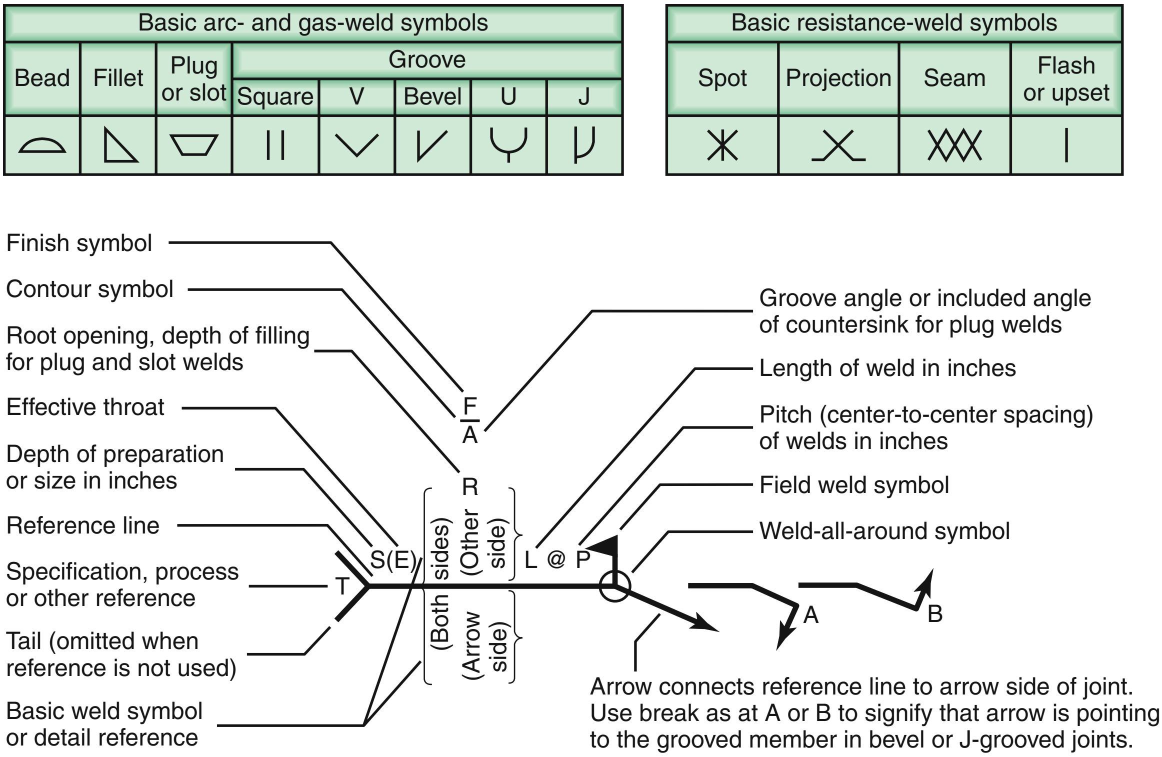


FIGURE 30.28 Standard identification and symbols for welds.

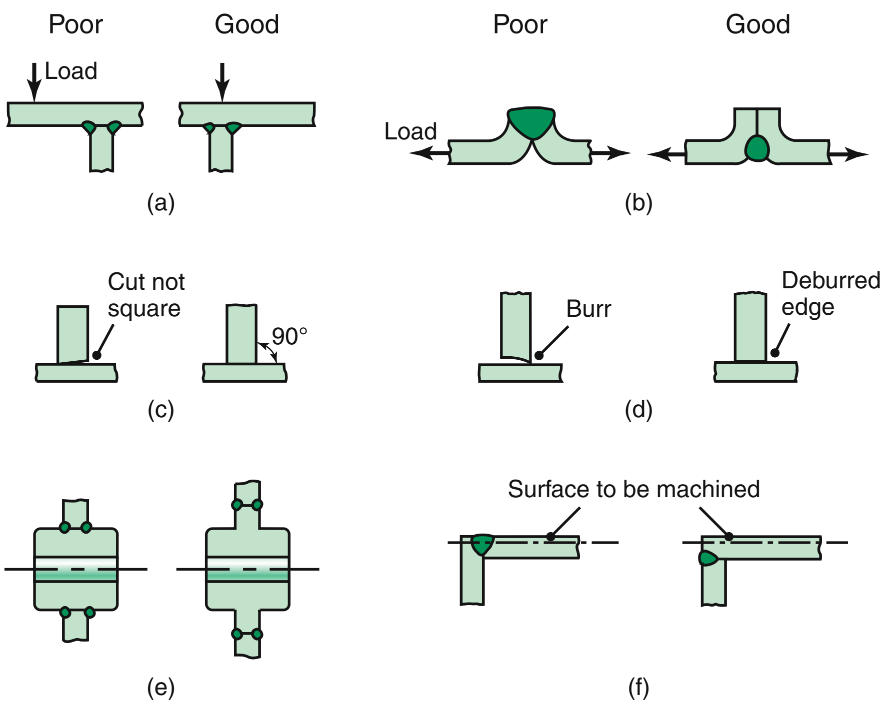


FIGURE 30.29 Some design guidelines for welds. *Source*: After J.G. Bralla.

- Costs involved in edge preparation, joining, and postprocessing (including machining, grinding, and finishing operations).
- Costs of equipment, materials, labor and skills required, and the joining operation.

Table VI.1 gave the various characteristics of individual welding processes—characteristics that would serve as an additional guide to process selection. Refering to this table, note that no single process has a high rating in all categories. For example,

- Arc welding, bolts, and riveting have high strength and reliability, but generally are not suitable for joining small parts.
- Resistance welding has strength and applications for both small and large parts. However, it is not easy to inspect visually for reliability, and resistance welding has lower tolerances and reliability than other processes.
- Fasteners are useful for large parts and can be easy to inspect visually, but they are costly and do not have much design variability.
- Adhesive bonding has high design variability. However, it has relatively low strength and is difficult to visually inspect for joint integrity.

EXAMPLE 30.3 Weld Design Selection

Three different types of weld designs are shown in Fig. 30.30. In Fig. 30.30a, the two vertical joints can be welded either externally or internally. Note that full-length external welding will take considerable time and will require more weld material than the alternative design, which consists of intermittent internal welds. Moreover, by the alternative method, the appearance of the structure is improved and distortion is reduced.

In Fig. 30.30b, it can be shown that the design on the right can carry three times the moment M of the one on the left. Note that both designs require the same amount of weld metal and welding time. In Fig. 30.30c, the weld on the left requires about twice the amount of weld material than does the design on the right. Note that because more material must be machined, the design on the left will require more time for edge preparation, and more base metal will be wasted as a result.

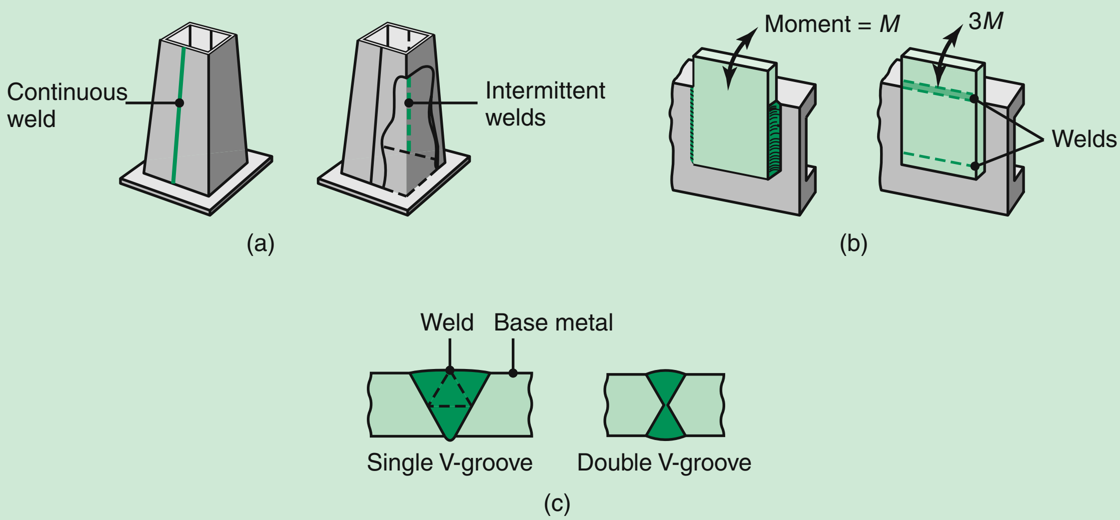


FIGURE 30.30 Examples of weld designs used in Example 30.3.

SUMMARY

- Oxyfuel–gas, arc, and high-energy-beam welding are among the most commonly used joining operations. Gas welding uses chemical energy; to supply the necessary heat, arc and high-energy-beam welding use electrical energy instead.
- In all of these processes, heat is used to bring the joint being welded to a liquid state. Shielding gases are used to protect the molten-weld pool and the weld area against oxidation. Filler rods may or may not be used in oxyfuel–gas and arc welding to fill the weld area.
- The selection of a welding process for a particular operation depends on the workpiece material, its thickness and size, its shape complexity, the type of joint, the strength required, and the change in product appearance caused by welding.
- A variety of welding equipment is available—much of which is now robotics and computer controlled with programmable features.
- The cutting of metals also can be done by processes whose principles are based on oxyfuel–gas and arc welding. The cutting of steels occurs mainly through oxidation (burning). The highest temperatures for cutting are obtained by plasma-arc cutting.
- The metallurgy of the welded joint is an important aspect of all welding processes, because it determines the strength and toughness of the joint. The welded joint consists of solidified metal and a heat-affected zone; each has a wide variation in microstructure and properties, depending on the metals joined and on the filler metals.
- The metallurgy of the welded joint is an important aspect of all welding processes, because it determines the strength and toughness of the joint. The welded joint consists of solidified metal and a heat-affected zone; each has a wide variation in microstructure and properties, depending on the metals joined and on the filler metals.
- Discontinuities such as porosity, inclusions, incomplete welds, tears, surface damage, and cracks can develop in the weld zone. Residual stresses and relieving them also are important considerations in welding.
- The weldability of metals and alloys depends greatly on their composition, the type of welding operation and process parameters employed, and the control of welding parameters.
- General guidelines are available to help in the initial selection of suitable and economical welding methods for a particular application.

KEY TERMS

Arc cutting
Arc welding
Atomic-hydrogen welding
Base metal
Carburizing flame
Coated electrode
Consumable electrode
Discontinuities
Drag lines
Electrode
Electrogas welding
Electron-beam welding
Electroslag welding
Filler metal
Flux
Flux-cored arc welding
Fusion welding
Gas metal-arc welding
Gas tungsten-arc welding
Heat-affected zone
Inclusions
Joining
Kerf
Keyhole technique
Laser-beam welding
Neutral flame
Nonconsumable electrode
Oxidizing flame
Oxyfuel–gas cutting
Oxyfuel–gas welding
Plasma-arc welding
Polarity
Porosity
Reducing flame
Residual stresses
Shielded metal-arc welding
Slag
Stick welding
Submerged-arc welding
Tears
Weld profile
Weld metal
Weldability
Welding gun