PART I

Introduction

1 Fusion Welding Processes

Fusion welding processes will be described in this chapter, including gas welding, arc welding, and high-energy beam welding. The advantages and disadvantages of each process will be discussed.

1.1 OVERVIEW

1.1.1 Fusion Welding Processes

Fusion welding is a joining process that uses fusion of the base metal to make the weld. The three major types of fusion welding processes are as follows:

1. **Gas welding**:
    Oxyacetylene welding (OAW)
2. **Arc welding**:
    Shielded metal arc welding (SMAW)
    Gas–tungsten arc welding (GTAW)
    Plasma arc welding (PAW)
    Gas–metal arc welding (GMAW)
    Flux-cored arc welding (FCAW)
    Submerged arc welding (SAW)
    Electroslag welding (ESW)
3. **High-energy beam welding**:
    Electron beam welding (EBW)
    Laser beam welding (LBW)

Since there is no arc involved in the electroslag welding process, it is not exactly an arc welding process. For convenience of discussion, it is grouped with arc welding processes.

1.1.2 Power Density of Heat Source

Consider directing a 1.5-kW hair drier very closely to a 304 stainless steel sheet 1.6 mm ($^1/_{16}$ in.) thick. Obviously, the power spreads out over an area of roughly

50 mm (2 in.) diameter, and the sheet just heats up gradually but will not melt. With GTAW at 1.5 kW, however, the arc concentrates on a small area of about 6 mm ($\frac{1}{4}$ in.) diameter and can easily produce a weld pool. This example clearly demonstrates the importance of the power density of the heat source in welding.

The heat sources for the gas, arc, and high-energy beam welding processes are a gas flame, an electric arc, and a high-energy beam, respectively. The power density increases from a gas flame to an electric arc and a high-energy beam. As shown in Figure 1.1, as the power density of the heat source increases, the heat input to the workpiece that is required for welding decreases. The portion of the workpiece material exposed to a gas flame heats up so slowly that, before any melting occurs, a large amount of heat is already conducted away into the bulk of the workpiece. Excessive heating can cause damage to the workpiece, including weakening and distortion. On the contrary, the same material exposed to a sharply focused electron or laser beam can melt or even vaporize to form a deep *keyhole* instantaneously, and before much heat is conducted away into the bulk of the workpiece, welding is completed (1).

Therefore, the advantages of increasing the power density of the heat source are deeper weld penetration, higher welding speeds, and better weld quality with less damage to the workpiece, as indicated in Figure 1.1. Figure 1.2 shows that the weld strength (of aluminum alloys) increases as the heat input per unit length of the weld per unit thickness of the workpiece decreases (2). Figure 1.3*a* shows that angular distortion is much smaller in EBW than in

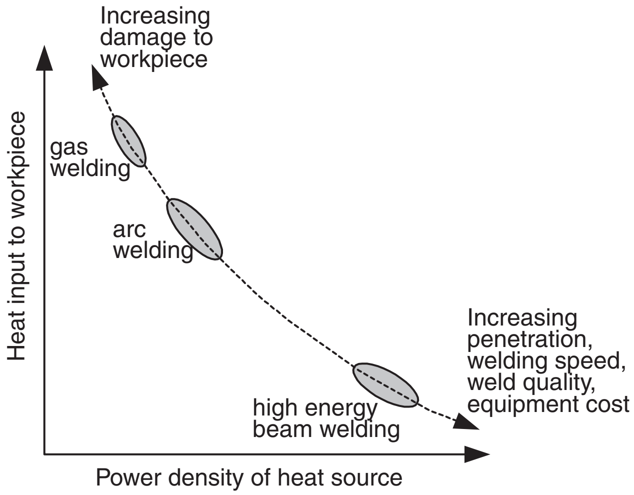

Figure 1.1 Variation of heat input to the workpiece with power density of the heat source.

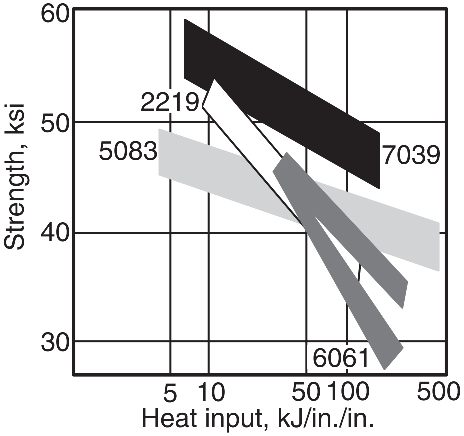

Figure 1.2 Variation of weld strength with heat input per unit length of weld per unit thickness of workpiece. Reprinted from Mendez and Eagar (2).

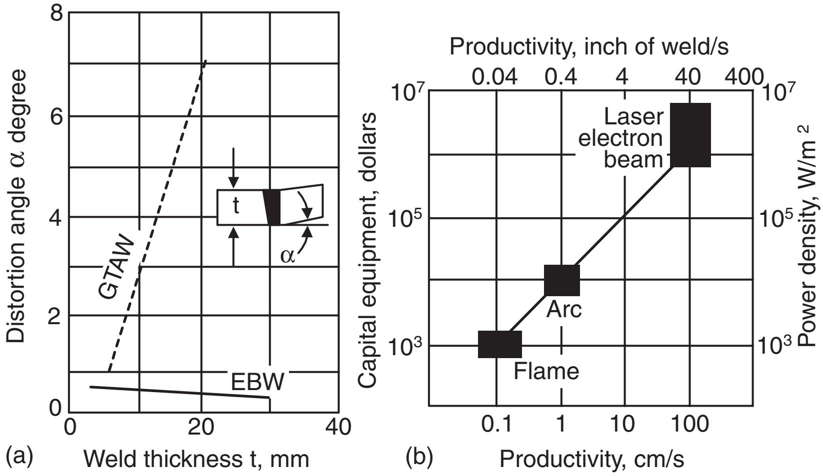

Figure 1.3 Comparisons between welding processes: (*a*) angular distortion; (*b*) capital equipment cost. Reprinted from Mendez and Eagar (2).

GTAW (2). Unfortunately, as shown in Figure 1.3*b*, the costs of laser and electron beam welding machines are very high (2).

1.1.3 Welding Processes and Materials

Table 1.1 summarizes the fusion welding processes recommended for carbon steels, low-alloy steels, stainless steels, cast irons, nickel-base alloys, and

TABLE 1.1 Overview of Welding Processes[a]

Material	Thickness[b]	SMAW	SAW	GMAW	FCAW	GTAW	PAW	ESW	OFW	EBW	LBW
Carbon steels	S	×	×	×		×			×	×	×
	I	×	×	×	×	×			×	×	×
	M	×	×	×	×				×	×	×
	T	×	×	×	×			×	×	×	
Low-alloy steels	S	×	×	×		×			×	×	×
	I	×	×	×	×	×				×	×
	M	×	×	×	×					×	×
	T	×	×	×	×			×		×	
Stainless steels	S	×	×	×		×	×		×	×	×
	I	×	×	×	×	×	×			×	×
	M	×	×	×	×		×			×	×
	T	×	×	×	×			×		×	
Cast iron	I	×							×		
	M	×	×	×	×				×		
	T	×	×	×	×				×		
Nickel and alloys	S	×		×		×	×		×	×	×
	I	×	×	×		×	×			×	×
	M	×	×	×			×			×	×
	T	×		×				×		×	
Aluminum and alloys	S			×		×	×		×	×	×
	I			×		×				×	×
	M			×		×				×	
	T			×						×	

[a] Process code: SMAW, shielded metal arc welding; SAW, submerged arc welding; GMAW, gas–metal arc welding; FCAW, flux-cored arc welding; GTAW, gas–tungsten arc welding; PAW, plasma arc welding; ESW, electroslag welding; OFW, oxyfuel gas welding; EBW, electron beam welding; LBW, laser beam welding.

[b] Abbreviations: S, sheet, up to 3 mm ($\frac{1}{8}$ in.); I, intermediate, 3–6 mm ($\frac{1}{8}$–$\frac{1}{4}$ in.); M, medium, 6–19 mm ($\frac{1}{4}$–$\frac{3}{4}$ in.); T, thick, 19 mm ($\frac{3}{4}$ in.) and up; X, recommended.

Source: *Welding Handbook* (3).

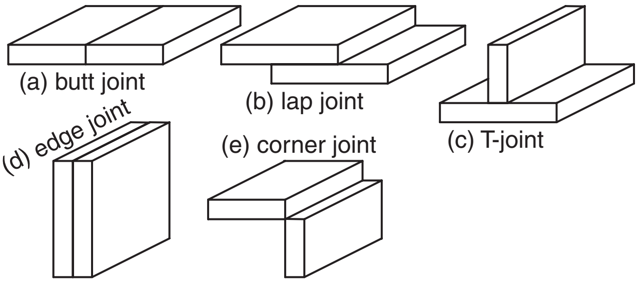

Figure 1.4 Five basic types of weld joint designs.

aluminum alloys (3). For one example, GMAW can be used for all the materials of almost all thickness ranges while GTAW is mostly for thinner workpieces. For another example, any arc welding process that requires the use of a flux, such as SMAW, SAW, FCAW, and ESW, is not applicable to aluminum alloys.

1.1.4 Types of Joints and Welding Positions

Figure 1.4 shows the basic weld joint designs in fusion welding: the butt, lap, T-, edge, and corner joints. Figure 1.5 shows the transverse cross section of some typical weld joint variations. The surface of the weld is called the face, the two junctions between the face and the workpiece surface are called the toes, and the portion of the weld beyond the workpiece surface is called the reinforcement. Figure 1.6 shows four welding positions.

1.2 OXYACETYLENE WELDING

1.2.1 The Process

Gas welding is a welding process that melts and joins metals by heating them with a flame caused by the reaction between a fuel gas and oxygen. Oxyacetylene welding (OAW), shown in Figure 1.7, is the most commonly used gas welding process because of its high flame temperature. A flux may be used to deoxidize and cleanse the weld metal. The flux melts, solidifies, and forms a slag skin on the resultant weld metal. Figure 1.8 shows three different types of flames in oxyacetylene welding: neutral, reducing, and oxidizing (4), which are described next.

1.2.2 Three Types of Flames

A. Neutral Flame This refers to the case where oxygen (O_2) and acetylene (C_2H_2) are mixed in equal amounts and burned at the tip of the welding torch. A short inner cone and a longer outer envelope characterize a neutral flame

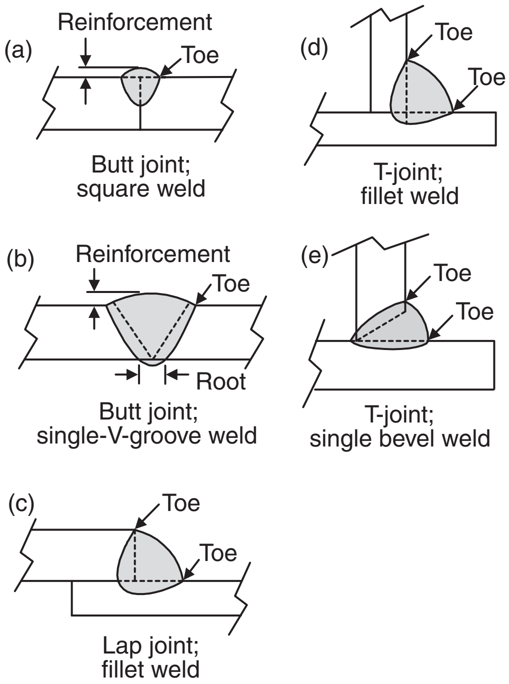

Figure 1.5 Typical weld joint variations.

(Figure 1.8*a*). The inner cone is the area where the primary combustion takes place through the chemical reaction between O_2 and C_2H_2, as shown in Figure 1.9. The heat of this reaction accounts for about two-thirds of the total heat generated. The products of the primary combustion, CO and H_2, react with O_2 from the surrounding air and form CO_2 and H_2O. This is the secondary combustion, which accounts for about one-third of the total heat generated. The area where this secondary combustion takes place is called the outer envelope. It is also called the protection envelope since CO and H_2 here consume the O_2 entering from the surrounding air, thereby protecting the weld metal from oxidation. For most metals, a neutral flame is used.

B. Reducing Flame When excess acetylene is used, the resulting flame is called a reducing flame. The combustion of acetylene is incomplete. As a result, a greenish acetylene feather between the inert cone and the outer envelope characterizes a reducing flame (Figure 1.8*b*). This flame is reducing in nature and is desirable for welding aluminum alloys because aluminum oxidizes easily. It is also good for welding high-carbon steels (also called carburizing flame in this case) because excess oxygen can oxidize carbon and form CO gas porosity in the weld metal.

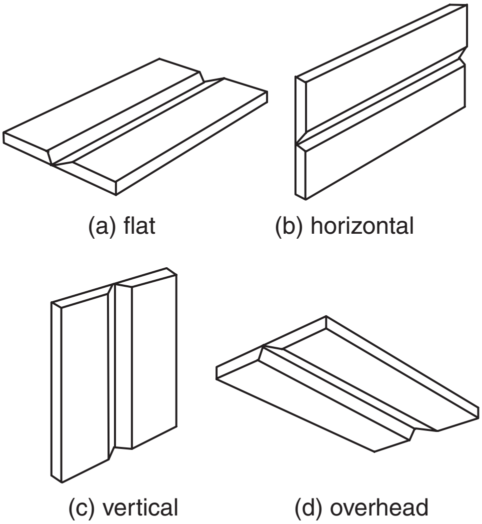

Figure 1.6 Four welding positions.

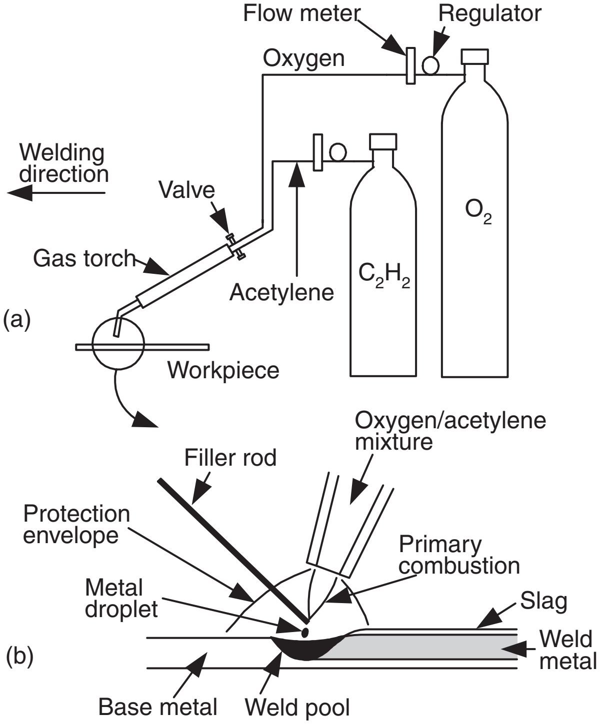

Figure 1.7 Oxyacetylene welding: (*a*) overall process; (*b*) welding area enlarged.

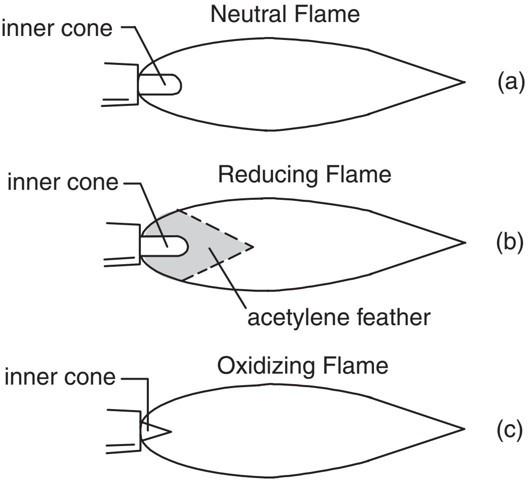

Figure 1.8 Three types of flames in oxyacetylene welding. Modified from *Welding Journal* (4). Courtesy of American Welding Society.

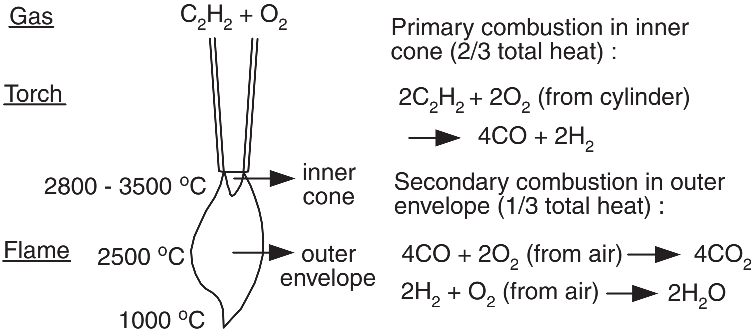

Figure 1.9 Chemical reactions and temperature distribution in a neutral oxyacetylene flame.

C. Oxidizing Flame When excess oxygen is used, the flame becomes oxidizing because of the presence of unconsumed oxygen. A short white inner cone characterizes an oxidizing flame (Figure 1.8*c*). This flame is preferred when welding brass because copper oxide covers the weld pool and thus prevents zinc from evaporating from the weld pool.

1.2.3 Advantages and Disadvantages

The main advantage of the oxyacetylene welding process is that the equipment is simple, portable, and inexpensive. Therefore, it is convenient for maintenance and repair applications. However, due to its limited power density, the welding speed is very low and the total heat input per unit length of the weld is rather high, resulting in large heat-affected zones and severe distortion. The oxyacetylene welding process is not recommended for welding reactive metals such as titanium and zirconium because of its limited protection power.

1.3 SHIELDED METAL ARC WELDING

1.3.1 The Process

Shielded metal arc welding (SMAW) is a process that melts and joins metals by heating them with an arc established between a sticklike covered electrode and the metals, as shown in Figure 1.10. It is often called *stick welding*. The electrode holder is connected through a welding cable to one terminal of the power source and the workpiece is connected through a second cable to the other terminal of the power source (Figure 1.10*a*).

The core of the covered electrode, the core wire, conducts the electric current to the arc and provides filler metal for the joint. For electrical contact, the top 1.5 cm of the core wire is bare and held by the electrode holder. The electrode holder is essentially a metal clamp with an electrically insulated outside shell for the welder to hold safely.

The heat of the arc causes both the core wire and the flux covering at the electrode tip to melt off as droplets (Figure 1.10*b*). The molten metal collects in the weld pool and solidifies into the weld metal. The lighter molten flux, on the other hand, floats on the pool surface and solidifies into a slag layer at the top of the weld metal.

1.3.2 Functions of Electrode Covering

The covering of the electrode contains various chemicals and even metal powder in order to perform one or more of the functions described below.

A. Protection It provides a gaseous shield to protect the molten metal from air. For a *cellulose*-type electrode, the covering contains cellulose, $(C_6H_{10}O_5)_x$. A large volume of gas mixture of H_2, CO, H_2O, and CO_2 is produced when cellulose in the electrode covering is heated and decomposes. For a *limestone*- ($CaCO_3$-) type electrode, on the other hand, CO_2 gas and CaO slag form when the limestone decomposes. The limestone-type electrode is a *low-hydrogen*-type electrode because it produces a gaseous shield low in hydrogen. It is often used for welding metals that are susceptible to hydrogen cracking, such as high-strength steels.

B. Deoxidation It provides deoxidizers and fluxing agents to deoxidize and cleanse the weld metal. The solid slag formed also protects the already solidified but still hot weld metal from oxidation.

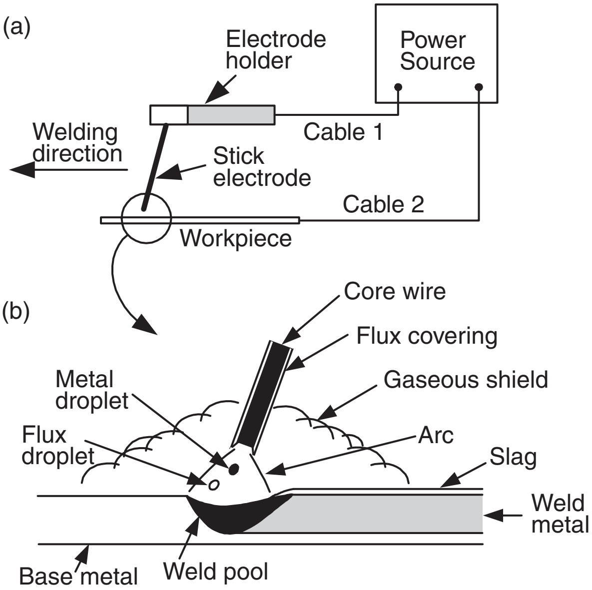

Figure 1.10 Shielded metal arc welding: (*a*) overall process; (*b*) welding area enlarged.

C. Arc Stabilization It provides arc stabilizers to help maintain a stable arc. The arc is an ionic gas (a plasma) that conducts the electric current. Arc stabilizers are compounds that decompose readily into ions in the arc, such as potassium oxalate and lithium carbonate. They increase the electrical conductivity of the arc and help the arc conduct the electric current more smoothly.

D. Metal Addition It provides alloying elements and/or metal powder to the weld pool. The former helps control the composition of the weld metal while the latter helps increase the deposition rate.

1.3.3 Advantages and Disadvantages

The welding equipment is relatively simple, portable, and inexpensive as compared to other arc welding processes. For this reason, SMAW is often used for maintenance, repair, and field construction. However, the gas shield in SMAW is not clean enough for reactive metals such as aluminum and titanium. The deposition rate is limited by the fact that the electrode covering tends to overheat and fall off when excessively high welding currents are used. The limited length of the electrode (about 35 cm) requires electrode changing, and this further reduces the overall production rate.

1.4 GAS–TUNGSTEN ARC WELDING

1.4.1 The Process

Gas–tungsten arc welding (GTAW) is a process that melts and joins metals by heating them with an arc established between a nonconsumable tungsten electrode and the metals, as shown in Figure 1.11. The torch holding the tungsten electrode is connected to a shielding gas cylinder as well as one terminal of the power source, as shown in Figure 1.11*a*. The tungsten electrode is usually in contact with a water-cooled copper tube, called the contact tube, as shown in Figure 1.11*b*, which is connected to the welding cable (cable 1) from the terminal. This allows both the welding current from the power source to enter the electrode and the electrode to be cooled to prevent overheating. The workpiece is connected to the other terminal of the power source through a different cable (cable 2). The shielding gas goes through the torch body and is directed by a nozzle toward the weld pool to protect it from the air. Protection from the air is much better in GTAW than in SMAW because an inert gas such as argon or helium is usually used as the shielding gas and because the shielding gas is directed toward the weld pool. For this reason, GTAW is

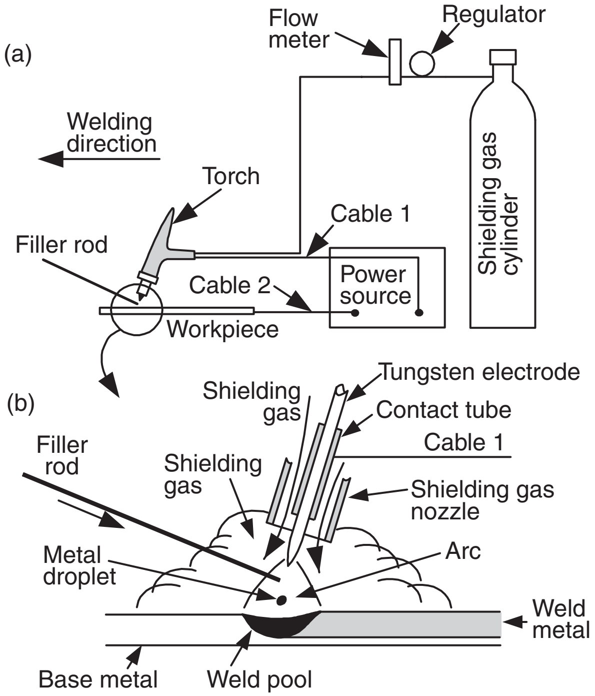

Figure 1.11 Gas–tungsten arc welding: (*a*) overall process; (*b*) welding area enlarged.

also called *tungsten–inert gas* (TIG) welding. However, in special occasions a noninert gas (Chapter 3) can be added in a small quantity to the shielding gas. Therefore, GTAW seems a more appropriate name for this welding process. When a filler rod is needed, for instance, for joining thicker materials, it can be fed either manually or automatically into the arc.

1.4.2 Polarity

Figure 1.12 shows three different polarities in GTAW (5), which are described next.

A. Direct-Current Electrode Negative (DCEN) This, also called the *straight polarity*, is the most common polarity in GTAW. The electrode is connected to the negative terminal of the power supply. As shown in Figure 1.12a, electrons are emitted from the tungsten electrode and accelerated while traveling through the arc. A significant amount of energy, called the work function, is required for an electron to be emitted from the electrode. When the electron enters the workpiece, an amount of energy equivalent to the work function is released. This is why in GTAW with DCEN more power (about two-thirds) is located at the work end of the arc and less (about one-third) at the electrode end. Consequently, a relatively narrow and deep weld is produced.

B. Direct-Current Electrode Positive (DCEP) This is also called the *reverse polarity*. The electrode is connected to the positive terminal of the power source. As shown in Figure 1.12b, the heating effect of electrons is now at the tungsten electrode rather than at the workpiece. Consequently, a shallow weld is produced. Furthermore, a large-diameter, water-cooled electrodes must be used in order to prevent the electrode tip from melting. The positive ions of the shielding gas bombard the workpiece, as shown in Figure 1.13, knocking off oxide films and producing a clean weld surface. Therefore, DCEP can be

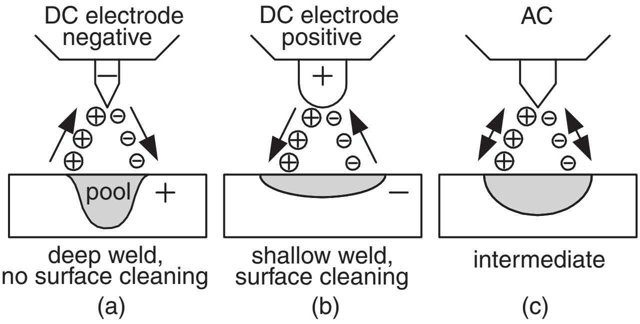

Figure 1.12 Three different polarities in GTAW.

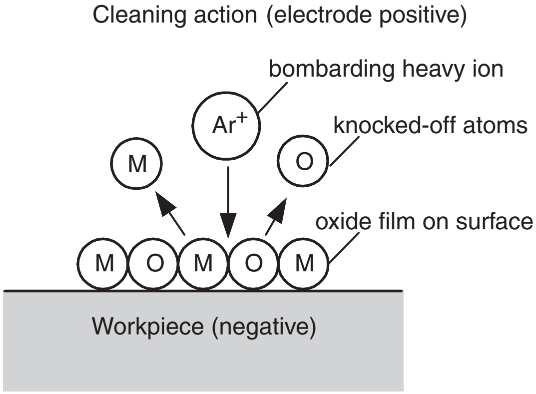

Figure 1.13 Surface cleaning action in GTAW with DC electrode positive.

used for welding thin sheets of strong oxide-forming materials such as aluminum and magnesium, where deep penetration is not required.

C. Alternating Current (AC) Reasonably good penetration and oxide cleaning action can both be obtained, as illustrated in Figure 1.12c. This is often used for welding aluminum alloys.

1.4.3 Electrodes

Tungsten electrodes with 2% cerium or thorium have better electron emissivity, current-carrying capacity, and resistance to contamination than pure tungsten electrodes (3). As a result, arc starting is easier and the arc is more stable. The electron emissivity refers to the ability of the electrode tip to emit electrons. A lower electron emissivity implies a higher electrode tip temperature required to emit electrons and hence a greater risk of melting the tip.

1.4.4 Shielding Gases

Both argon and helium can be used. Table 1.2 lists the properties of some shielding gases (6). As shown, the *ionization potentials* for argon and helium are 15.7 and 24.5 eV (electron volts), respectively. Since it is easier to ionize argon than helium, arc initiation is easier and the voltage drop across the arc is lower with argon. Also, since argon is heavier than helium, it offers more effective shielding and greater resistance to cross draft than helium. With DCEP or AC, argon also has a greater oxide cleaning action than helium. These advantages plus the lower cost of argon make it more attractive for GTAW than helium.

TABLE 1.2 Properties of Shielding Gases Used for Welding

Gas	Chemical Symbol	Molecular Weight (g/mol)	Specific Gravity with Respect to Air at 1 atm and 0°C	Density (g/L)	Ionization Potential (eV)
Argon	Ar	39.95	1.38	1.784	15.7
Carbon dioxide	CO_2	44.01	1.53	1.978	14.4
Helium	He	4.00	0.1368	0.178	24.5
Hydrogen	H_2	2.016	0.0695	0.090	13.5
Nitrogen	N_2	28.01	0.967	1.25	14.5
Oxygen	O_2	32.00	1.105	1.43	13.2

Source: Reprinted from Lyttle (6).

Because of the greater voltage drop across a helium arc than an argon arc, however, higher power inputs and greater sensitivity to variations in the arc length can be obtained with helium. The former allows the welding of thicker sections and the use of higher welding speeds. The latter, on the other hand, allows a better control of the arc length during automatic GTAW.

1.4.5 Advantages and Disadvantages

Gas–tungsten arc welding is suitable for joining thin sections because of its limited heat inputs. The feeding rate of the filler metal is somewhat independent of the welding current, thus allowing a variation in the relative amount of the fusion of the base metal and the fusion of the filler metal. Therefore, the control of dilution and energy input to the weld can be achieved without changing the size of the weld. It can also be used to weld butt joints of thin sheets by fusion alone, that is, without the addition of filler metals or *autogenous* welding. Since the GTAW process is a very clean welding process, it can be used to weld reactive metals, such as titanium and zirconium, aluminum, and magnesium.

However, the deposition rate in GTAW is low. Excessive welding currents can cause melting of the tungsten electrode and results in brittle tungsten inclusions in the weld metal. However, by using preheated filler metals, the deposition rate can be improved. In the hot-wire GTAW process, the wire is fed into and in contact with the weld pool so that resistance heating can be obtained by passing an electric current through the wire.

1.5 PLASMA ARC WELDING

1.5.1 The Process

Plasma arc welding (PAW) is an arc welding process that melts and joins metals by heating them with a constricted arc established between a tungsten electrode and the metals, as shown in Figure 1.14. It is similar to GTAW, but an orifice gas as well as a shielding gas is used. As shown in Figure 1.15, the arc in PAW is constricted or collimated because of the converging action of the orifice gas nozzle, and the arc expands only slightly with increasing arc length (5). Direct-current electrode negative is normally used, but a special variable-polarity PAW machine has been developed for welding aluminum, where the presence of aluminum oxide films prevents a keyhole from being established.

1.5.2 Arc Initiation

The tungsten electrode sticks out of the shielding gas nozzle in GTAW (Figure 1.11*b*) while it is recessed in the orifice gas nozzle in PAW (Figure 1.14*b*). Consequently, arc initiation cannot be achieved by striking the electrode tip against the workpiece as in GTAW. The control console (Figure 1.14*a*) allows a pilot arc to be initiated, with the help of a high-frequency generator, between the electrode tip and the water-cooled orifice gas nozzle. The arc is then gradually

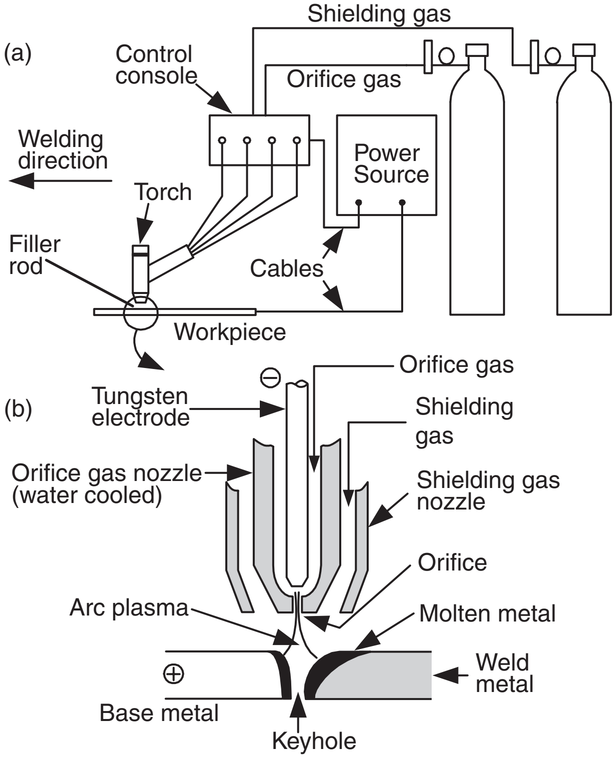

Figure 1.14 Plasma arc welding: (*a*) overall process; (*b*) welding area enlarged and shown with keyholing.

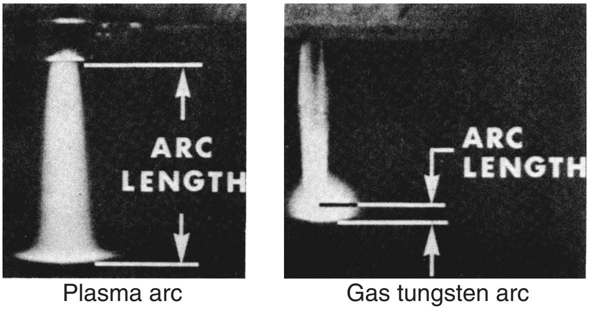

Figure 1.15 Comparison between a gas–tungsten arc and a plasma arc. From *Welding Handbook* (5). Courtesy of American Welding Society.

transferred from between the electrode tip and the orifice gas nozzle to between the electrode tip and the workpiece.

1.5.3 Keyholing

In addition to the *melt-in mode* adopted in conventional arc welding processes (such as GTAW), the *keyholing mode* can also be used in PAW in certain ranges of metal thickness (e.g., 2.5–6.4 mm). With proper combinations of the orifice gas flow, the travel speed, and the welding current, keyholing is possible. Keyholing is a positive indication of full penetration and it allows the use of significantly higher welding speeds than GTAW. For example, it has been reported (7) that PAW took one-fifth to one-tenth as long to complete a 2.5-m-long weld in 6.4-mm-thick 410 stainless steel as GTAW. Gas–tungsten arc welding requires multiple passes and is limited in welding speed. As shown in Figure 1.16, 304 stainless steel up to 13 mm ($\frac{1}{2}$ in.) thick can be welded in a single pass (8). The wine-cup-shaped weld is common in keyholing PAW.

1.5.4 Advantages and Disadvantages

Plasma arc welding has several advantages over GTAW. With a collimated arc, PAW is less sensitive to unintentional arc length variations during manual welding and thus requires less operator skill than GTAW. The short arc length in GTAW can cause a welder to unintentionally touch the weld pool with the electrode tip and contaminate the weld metal with tungsten. However, PAW does not have this problem since the electrode is recessed in the nozzle. As already mentioned, the keyhole is a positive indication of full penetration, and it allows higher welding speeds to be used in PAW.

However, the PAW torch is more complicated. It requires proper electrode tip configuration and positioning, selection of correct orifice size for the application, and setting of both orifice and shielding gas flow rates. Because of the

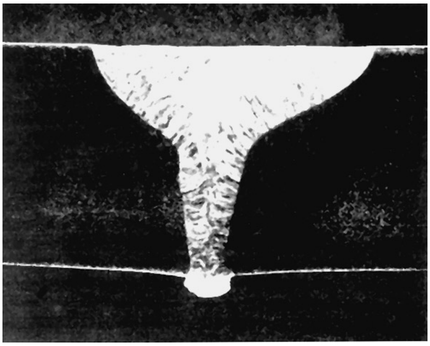

Figure 1.16 A plasma arc weld made in 13-mm-thick 304 stainless steel with keyholing. From Lesnewich (8).

need for a control console, the equipment cost is higher in PAW than in GTAW. The equipment for variable-polarity PAW is much more expensive than that for GTAW.

1.6 GAS–METAL ARC WELDING

1.6.1 The Process

Gas–metal arc welding (GMAW) is a process that melts and joins metals by heating them with an arc established between a continuously fed filler wire electrode and the metals, as shown in Figure 1.17. Shielding of the arc and the molten weld pool is often obtained by using inert gases such as argon and helium, and this is why GMAW is also called the *metal–inert gas* (MIG) welding process. Since noninert gases, particularly CO_2, are also used, GMAW seems a more appropriate name. This is the most widely used arc welding process for aluminum alloys. Figure 1.18 shows gas–metal arc welds of 5083 aluminum, one made with Ar shielding and the other with 75% He–25% Ar shielding (9). Unlike in GTAW, DCEP is used in GMAW. A stable arc, smooth metal transfer with low spatter loss and good weld penetration can be obtained. With DCEN or AC, however, metal transfer is erratic.

1.6.2 Shielding Gases

Argon, helium, and their mixtures are used for nonferrous metals as well as stainless and alloy steels. The arc energy is less uniformly dispersed in an Ar arc than in a He arc because of the lower thermal conductivity of Ar. Consequently, the Ar arc plasma has a very high energy core and an outer mantle of lesser thermal energy. This helps produce a stable, axial transfer of metal

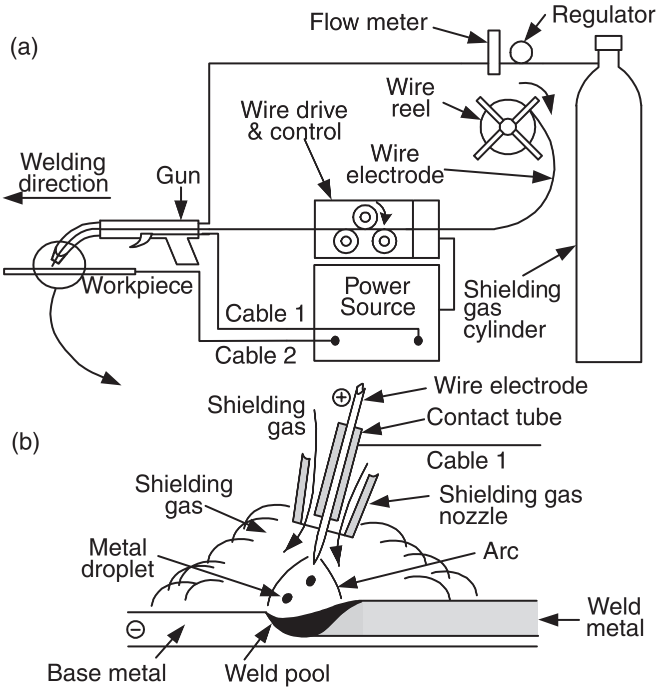

Figure 1.17 Gas–metal arc welding: (*a*) overall process; (*b*) welding area enlarged.

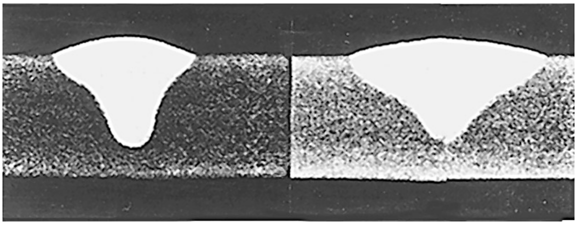

Figure 1.18 Gas–metal arc welds in 6.4-mm-thick 5083 aluminum made with argon (left) and 75% He–25% Ar (right). Reprinted from Gibbs (9). Courtesy of American Welding Society.

droplets through an Ar arc plasma. The resultant weld transverse cross section is often characterized by a papillary- (nipple-) type penetration pattern (10) such as that shown in Figure 1.18 (left). With pure He shielding, on the other hand, a broad, parabolic-type penetration is often observed.

With ferrous metals, however, He shielding may produce spatter and Ar shielding may cause undercutting at the fusion lines. Adding O_2 (about 3%) or CO_2 (about 9%) to Ar reduces the problems. Carbon and low-alloy steels are often welded with CO_2 as the shielding gas, the advantages being higher welding speed, greater penetration, and lower cost. Since CO_2 shielding produces a high level of spatter, a relatively low voltage is used to maintain a short buried arc to minimize spatter; that is, the electrode tip is actually below the workpiece surface (10).

1.6.3 Modes of Metal Transfer

The molten metal at the electrode tip can be transferred to the weld pool by three basic transfer modes: globular, spray, and short-circuiting.

A. Globular Transfer Discrete metal drops close to or larger than the electrode diameter travel across the arc gap under the influence of gravity. Figure 1.19*a* shows globular transfer during GMAW of steel at 180 A and with Ar–2% O_2 shielding (11). Globular transfer often is not smooth and produces spatter. At relatively low welding current globular transfer occurs regardless of the type of the shielding gas. With CO_2 and He, however, it occurs at all usable welding currents. As already mentioned, a short buried arc is used in CO_2-shielded GMAW of carbon and low-alloy steels to minimize spatter.

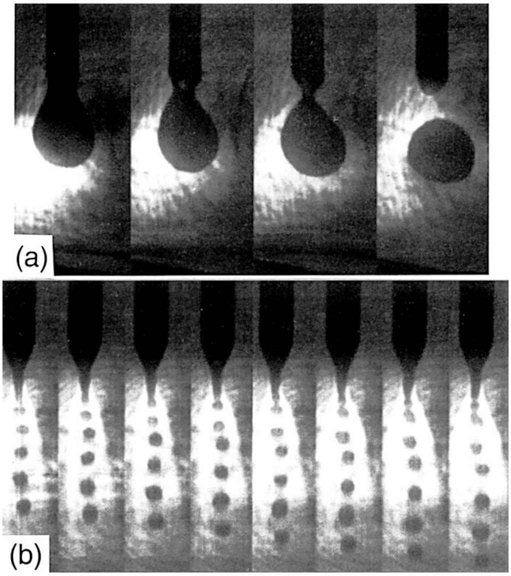

Figure 1.19 Metal transfer during GMAW of steel with Ar–2% O_2 shielding: (*a*) globular transfer at 180 A and 29 V shown at every 3×10^{-3} s; (*b*) spray transfer at 320 A and 29 V shown at every 2.5×10^{-4} s. Reprinted from Jones et al. (11). Courtesy of American Welding Society.

B. Spray Transfer Above a critical current level, small discrete metal drops travel across the arc gap under the influence of the electromagnetic force at much higher frequency and speed than in the globular mode. Figure 1.19*b* shows spray transfer during GMAW of steel at 320 A and with Ar–2% O_2 shielding (11). Metal transfer is much more stable and spatter free. The critical current level depends on the material and size of the electrode and the composition of the shielding gas. In the case of Figure 1.19, the critical current was found to be between 280 and 320 A (11).

C. Short-Circuiting Transfer The molten metal at the electrode tip is transferred from the electrode to the weld pool when it touches the pool surface, that is, when short circuiting occurs. Short-circuiting transfer encompasses the lowest range of welding currents and electrode diameters. It produces a small and fast-freezing weld pool that is desirable for welding thin sections, out-of-position welding (such as overhead-position welding), and bridging large root openings.

1.6.4 Advantages and Disadvantages

Like GTAW, GMAW can be very clean when using an inert shielding gas. The main advantage of GMAW over GTAW is the much higher deposition rate, which allows thicker workpieces to be welded at higher welding speeds. The dual-torch and twin-wire processes further increase the deposition rate of GMAW (12). The skill to maintain a very short and yet stable arc in GTAW is not required. However, GMAW guns can be bulky and difficult-to-reach small areas or corners.

1.7 FLUX-CORE ARC WELDING

1.7.1 The Process

Flux-core arc welding (FCAW) is similar to GMAW, as shown in Figure 1.20*a*. However, as shown in Figure 1.20*b*, the wire electrode is flux cored rather than solid; that is, the electrode is a metal tube with flux wrapped inside. The functions of the flux are similar to those of the electrode covering in SMAW, including protecting the molten metal from air. The use of additional shielding gas is optional.

1.8 SUBMERGED ARC WELDING

1.8.1 The Process

Submerged arc welding (SAW) is a process that melts and joins metals by heating them with an arc established between a consumable wire electrode

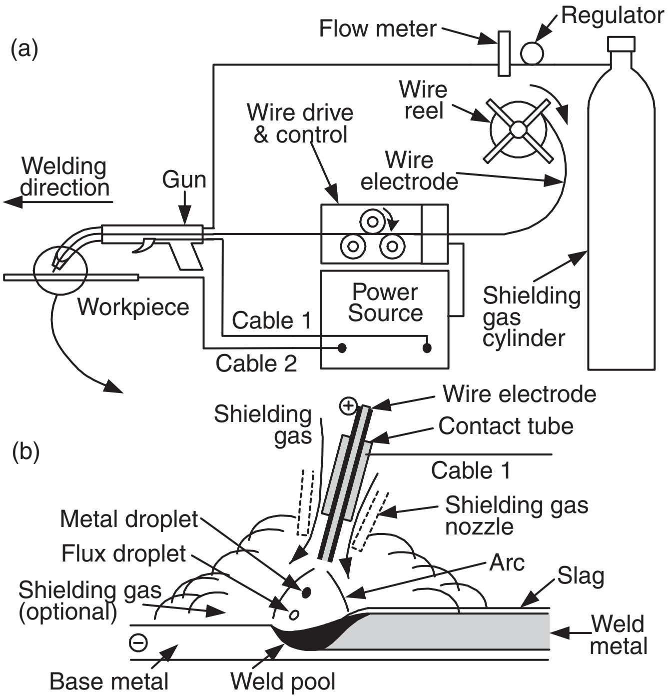

Figure 1.20 Flux-core arc welding: (*a*) overall process; (*b*) welding area enlarged.

and the metals, with the arc being shielded by a molten slag and granular flux, as shown in Figure 1.21. This process differs from the arc welding processes discussed so far in that the arc is submerged and thus invisible. The flux is supplied from a hopper (Figure 1.21*a*), which travels with the torch. No shielding gas is needed because the molten metal is separated from the air by the molten slag and granular flux (Figure 1.21*b*). Direct-current electrode positive is most often used. However, at very high welding currents (e.g., above 900 A) AC is preferred in order to minimize arc blow. Arc blow is caused by the electromagnetic (Lorentz) force as a result of the interaction between the electric current itself and the magnetic field it induces.

1.8.2 Advantages and Disadvantages

The protecting and refining action of the slag helps produce clean welds in SAW. Since the arc is submerged, spatter and heat losses to the surrounding air are eliminated even at high welding currents. Both alloying elements and metal powders can be added to the granular flux to control the weld metal composition and increase the deposition rate, respectively. Using two or more electrodes in tandem further increases the deposition rate. Because of its high

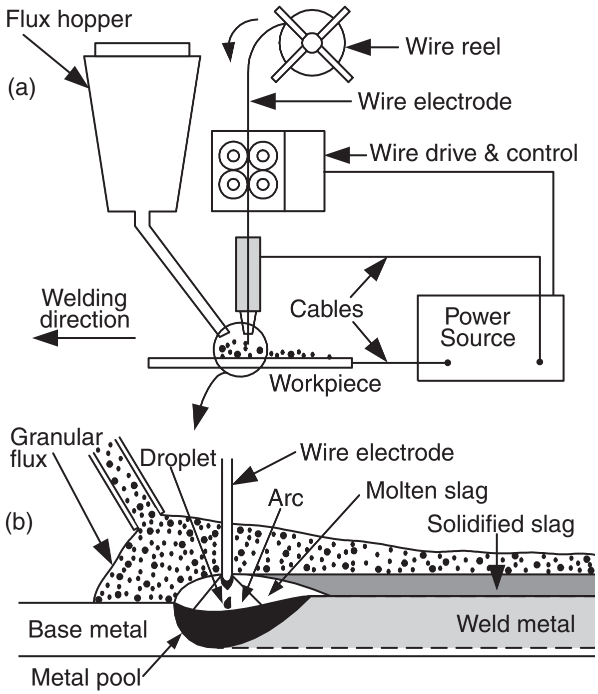

Figure 1.21 Submerged arc welding: (*a*) overall process; (*b*) welding area enlarged.

deposition rate, workpieces much thicker than that in GTAW and GMAW can be welded by SAW. However, the relatively large volumes of molten slag and metal pool often limit SAW to flat-position welding and circumferential welding (of pipes). The relatively high heat input can reduce the weld quality and increase distortions.

1.9 ELECTROSLAG WELDING

1.9.1 The Process

Electroslag welding (ESW) is a process that melts and joins metals by heating them with a pool of molten slag held between the metals and continuously feeding a filler wire electrode into it, as shown in Figure 1.22. The weld pool is covered with molten slag and moves upward as welding progresses. A pair of water-cooled copper shoes, one in the front of the workpiece and one behind it, keeps the weld pool and the molten slag from breaking out. Similar to SAW, the molten slag in ESW protects the weld metal from air and refines it. Strictly speaking, however, ESW is not an arc welding process, because the arc exists only during the initiation period of the process, that is, when the arc

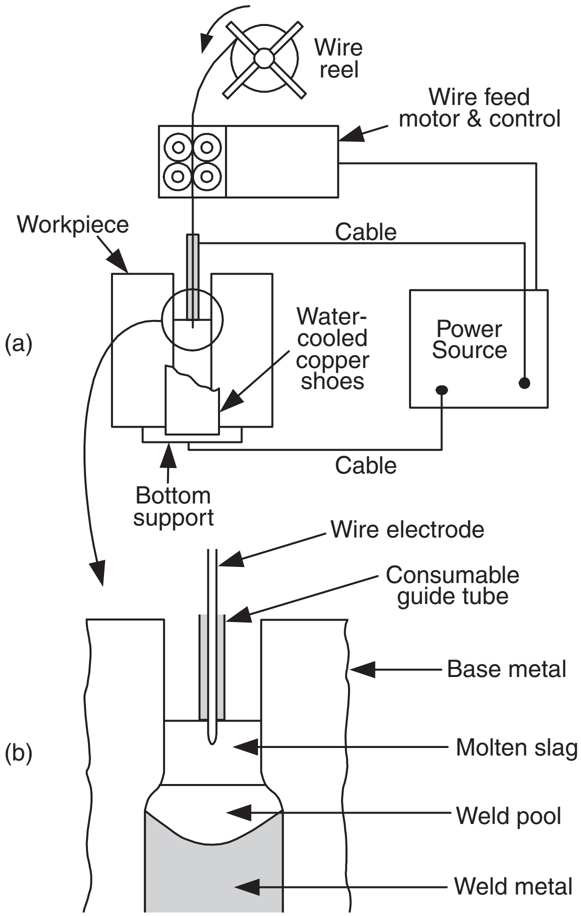

Figure 1.22 Electroslag welding: (*a*) overall process; (*b*) welding area enlarged.

heats up the flux and melts it. The arc is then extinguished, and the resistance heating generated by the electric current passing through the slag keeps it molten. In order to make heating more uniform, the electrode is often oscillated, especially when welding thicker sections. Figure 1.23 is the transverse cross section of an electroslag weld in a steel 7 cm thick (13). Typical examples of the application of ESW include the welding of ship hulls, storage tanks, and bridges.

1.9.2 Advantages and Disadvantages

Electroslag welding can have extremely high deposition rates, but only one single pass is required no matter how thick the workpiece is. Unlike SAW or other arc welding processes, there is no angular distortion in ESW because the

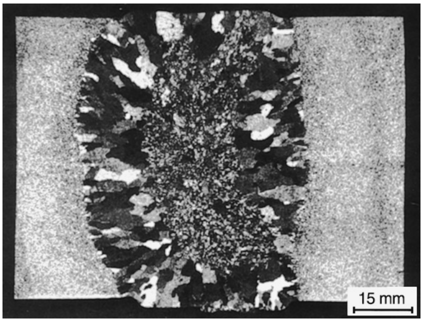

Figure 1.23 Transverse cross section of electroslag weld in 70-mm-thick steel. Reprinted from Eichhorn et al. (13). Courtesy of American Welding Society.

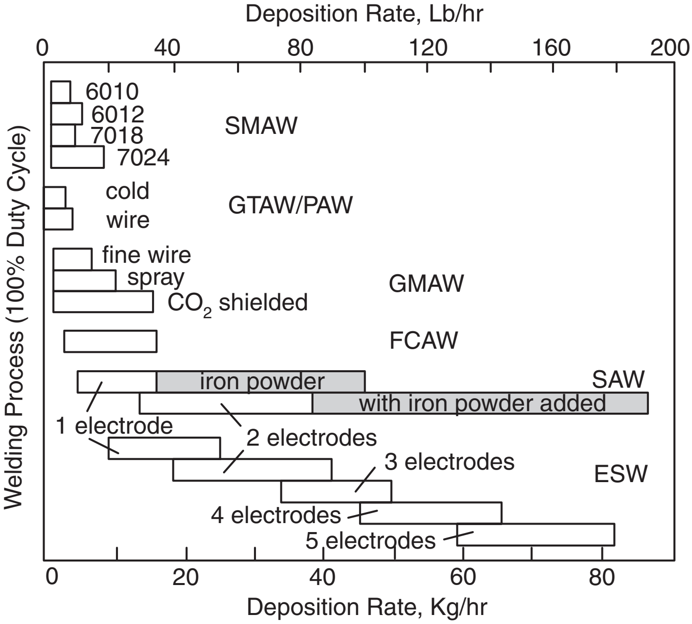

Figure 1.24 Deposition rate in arc welding processes. Modified from Cary (14).

weld is symmetrical with respect to its axis. However, the heat input is very high and the weld quality can be rather poor, including low toughness caused by the coarse grains in the fusion zone and the heat-affected zone. Electroslag welding is restricted to vertical position welding because of the very large pools of the molten metal and slag.

Figure 1.24 summarizes the deposition rates of the arc welding processes discussed so far (14). As shown, the deposition rate increases in the order of

GTAW, SMAW, GMAW and FCAW, SAW, and ESW. The deposition rate can be much increased by adding iron powder in SAW or using more than one wire in SAW, ESW, and GMAW (not shown).

1.10 ELECTRON BEAM WELDING

1.10.1 The Process

Electron beam welding (EBW) is a process that melts and joins metals by heating them with an electron beam. As shown in Figure 1.25*a*, the cathode of the electron beam gun is a negatively charged filament (15). When heated up to its thermionic emission temperature, this filament emits electrons. These electrons are accelerated by the electric field between a negatively charged bias electrode (located slightly below the cathode) and the anode. They pass through the hole in the anode and are focused by an electromagnetic coil to a point at the workpiece surface. The beam currents and the accelerating voltages employed for typical EBW vary over the ranges of 50–1000 mA and 30–175 kV, respectively. An electron beam of very high intensity can vaporize the metal and form a vapor hole during welding, that is, a keyhole, as depicted in Figure 1.25*b*.

Figure 1.26 shows that the beam diameter decreases with decreasing ambient pressure (1). Electrons are scattered when they hit air molecules, and the lower the ambient pressure, the less they are scattered. This is the main reason for EBW in a vacuum chamber.

The electron beam can be focused to diameters in the range of 0.3–0.8 mm and the resulting power density can be as high as 10^{10} W/m^2 (1). The very high

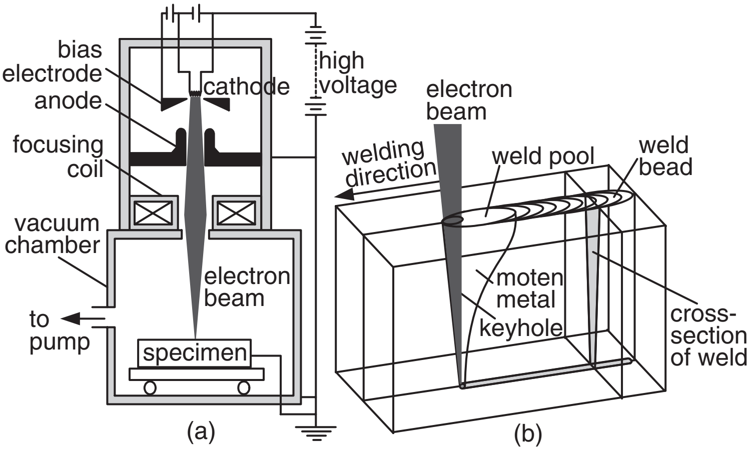

Figure 1.25 Electron beam welding: (*a*) process; (*b*) keyhole. Modified from Arata (15).

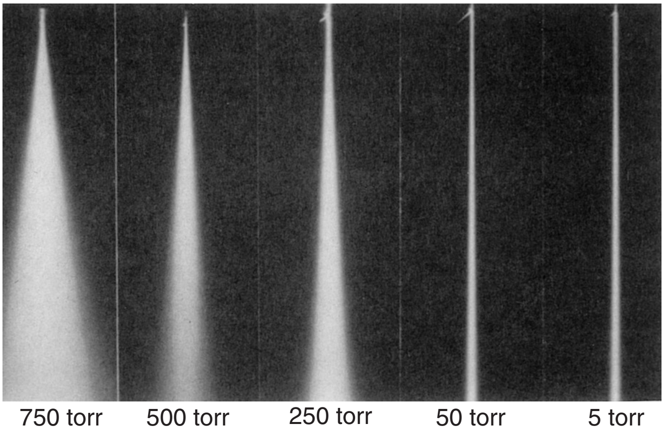

Figure 1.26 Dispersion of electron beam at various ambient pressures (1). Reprinted from *Welding Handbook* (1). Courtesy of American Welding Society.

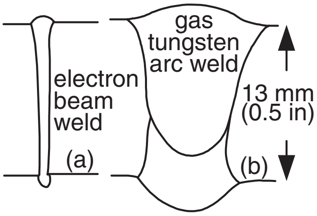

Figure 1.27 Welds in 13-mm-thick 2219 aluminum: (*a*) electron beam weld; (*b*) gas–tungsten arc weld. From Farrell (16).

power density makes it possible to vaporize the material and produce a deep-penetrating keyhole and hence weld. Figure 1.27 shows a single-pass electron beam weld and a dual-pass gas–tungsten arc weld in a 13-mm-thick (0.5-in.) 2219 aluminum, the former being much narrower (16). The energy required per unit length of the weld is much lower in the electron beam weld (1.5 kJ/cm, or 3.8 kJ/in.) than in the gas–tungsten arc weld (22.7 kJ/cm, or 57.6 kJ/in.).

Electron beam welding is not intended for incompletely degassed materials such as rimmed steels. Under high welding speeds gas bubbles that do not have enough time to leave deep weld pools result in weld porosity. Materials containing high-vapor-pressure constituents, such as Mg alloys and Pb-containing alloys, are not recommended for EBW because evaporation of these elements tends to foul the pumps or contaminate the vacuum system.

1.10.2 Advantages and Disadvantages

With a very high power density in EBW, full-penetration keyholing is possible even in thick workpieces. Joints that require multiple-pass arc welding can

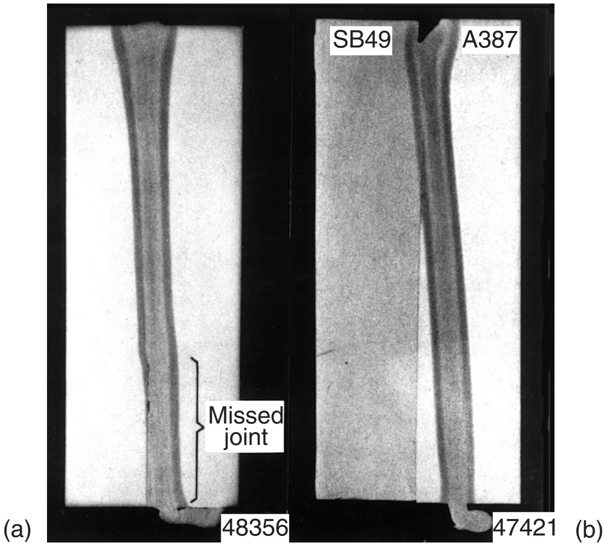

Figure 1.28 Missed joints in electron beam welds in 150-mm-thick steels: (*a*) 2.25Cr–1Mo steel with a transverse flux density of 3.5 G parallel to joint plane; (*b*) SB (C–Mn) steel and A387 (2.25Cr–1Mo) steel. Reprinted from Blakeley and Sanderson (17). Courtesy of American Welding Society.

be welded in a single pass at a high welding speed. Consequently, the total heat input per unit length of the weld is much lower than that in arc welding, resulting in a very narrow heat-affected zone and little distortion. Reactive and refractory metals can be welded in vacuum where there is no air to cause contamination. Some dissimilar metals can also be welded because the very rapid cooling in EBW can prevent the formation of coarse, brittle intermetallic compounds. When welding parts varying greatly in mass and size, the ability of the electron beam to precisely locate the weld and form a favorably shaped fusion zone helps prevent excessive melting of the smaller part.

However, the equipment cost for EBW is very high. The requirement of high vacuum (10^{-3}–10^{-6} torr) and x-ray shielding is inconvenient and time consuming. For this reason, medium-vacuum (10^{-3}–25 torr) EBW and nonvacuum (1 atm) EBW have also been developed. The fine beam size requires precise fit-up of the joint and alignment of the joint with the gun. As shown in Figure 1.28, residual and dissimilar metal magnetism can cause beam deflection and result in missed joints (17).

1.11 LASER BEAM WELDING

1.11.1 The Process

Laser beam welding (LBW) is a process that melts and joins metals by heating them with a laser beam. The laser beam can be produced either by a solid-state laser or a gas laser. In either case, the laser beam can be focused and directed by optical means to achieve high power densities. In a solid-state laser, a single crystal is doped with small concentrations of transition elements or rare earth elements. For instance, in a *YAG laser* the crystal of yttrium–aluminum–garnet (YAG) is doped with neodymium. The electrons of the dopant element can be selectively excited to higher energy levels upon exposure to high-intensity flash lamps, as shown in Figure 1.29*a*. Lasing occurs when these excited electrons return to their normal energy state, as shown in Figure 1.29*b*. The power level of solid-state lasers has improved significantly, and continuous YAG lasers of 3 or even 5 kW have been developed.

In a *CO_2 laser*, a gas mixture of CO_2, N_2, and He is continuously excited by electrodes connected to the power supply and lases continuously. Higher

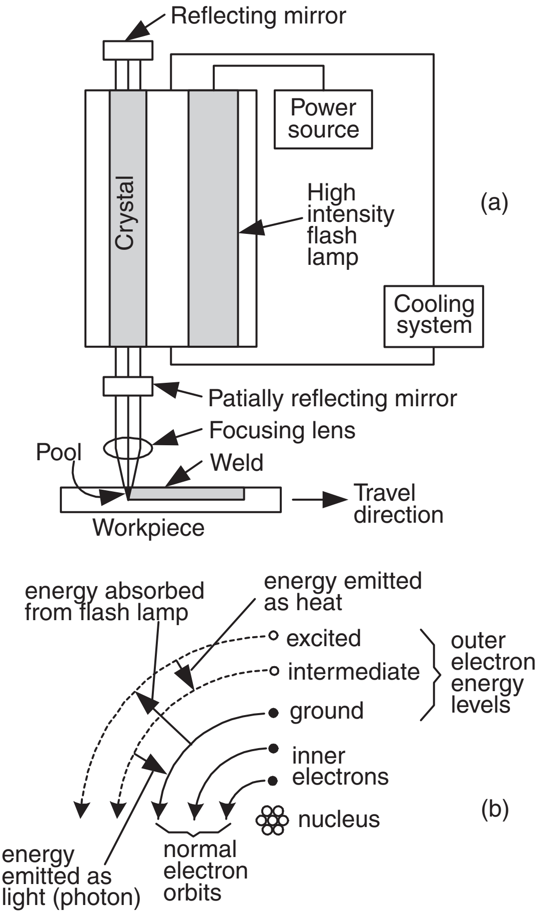

Figure 1.29 Laser beam welding with solid-state laser: (*a*) process; (*b*) energy absorption and emission during laser action. Modified from *Welding Handbook* (1).

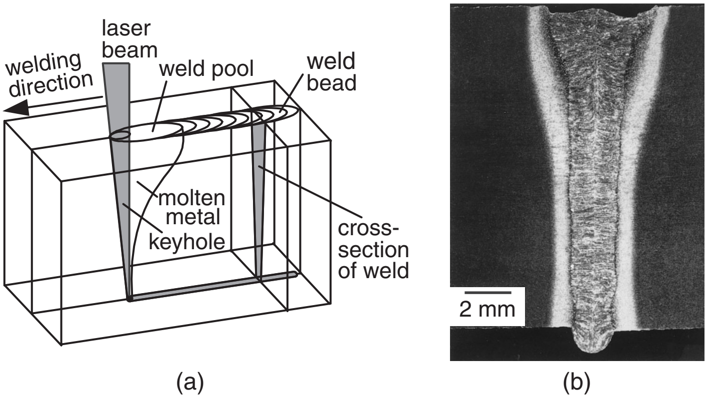

Figure 1.30 Laser beam welding with CO_2 laser: (*a*) process; (*b*) weld in 13-mm-thick A633 steel. (*b*) Courtesy of E.A. Metzbower.

power can be achieved by a CO_2 laser than a solid-state laser, for instance, 15 kW. Figure 1.30*a* shows LBW in the keyholing mode. Figure 1.30*b* shows a weld in a 13-mm-thick A633 steel made with a 15-kW CO_2 laser at 20 mm/s (18).

Besides solid-state and gas lasers, semiconductor-based *diode lasers* have also been developed. Diode lasers of 2.5 kW power and 1 mm focus diameter have been demonstrated (19). While keyholing is not yet possible, conduction-mode (surface melting) welding has produced full-penetration welds with a depth–width ratio of 3 : 1 or better in 3-mm-thick sheets.

1.11.2 Reflectivity

The very high reflectivity of a laser beam by the metal surface is a well-known problem in LBW. As much as about 95% of the CO_2 beam power can be reflected by a polished metal surface. Reflectivity is slightly lower with a YAG laser beam. Surface modifications such as roughening, oxidizing, and coating can reduce reflectivity significantly (20). Once keyholing is established, absorption is high because the beam is trapped inside the hole by internal reflection.

1.11.3 Shielding Gas

A plasma (an ionic gas) is produced during LBW, especially at high power levels, due to ionization by the laser beam. The plasma can absorb and scatter the laser beam and reduce the depth of penetration significantly. It is therefore necessary to remove or suppress the plasma (21). The shielding gas for protecting the molten metal can be directed sideways to blow and deflect the plasma away from the beam path. Helium is often preferred to argon as the shielding gas for high-power LBW because of greater penetration depth (22).

Since the ionization energy of helium (24.5 eV) is higher than that of argon (15.7 eV), helium is less likely to be ionized and become part of the plasma than argon. However, helium is lighter than air and is thus less effective in displacing air from the beam path. Helium–10% Ar shielding has been found to improve penetration over pure He at high-speed welding where a light shielding gas may not have enough time to displace air from the beam path (23).

1.11.4 Lasers in Arc Welding

As shown in Figure 1.31, laser-assisted gas metal arc welding (LAGMAW) has demonstrated significantly greater penetration than conventional GMAW (24). In addition to direct heating, the laser beam acts to focus the arc by heating its path through the arc. This increases ionization and hence the conductivity of the arc along the beam path and helps focus the arc energy along the path. It has been suggested that combining the arc power with a 5-kW CO_2 laser, LAGMAW has the potential to achieve weld penetration in mild steel equivalent to that of a 20–25-kW laser (24). Albright et al. (25) have shown that a lower power CO (not CO_2) laser of 7 W and 1 mm diameter can initiate, guide, and focus an Ar–1% CO gas–tungsten arc.

1.11.5 Advantages and Disadvantages

Like EBW, LBW can produce deep and narrow welds at high welding speeds, with a narrow heat-affected zone and little distortion of the workpiece. It can

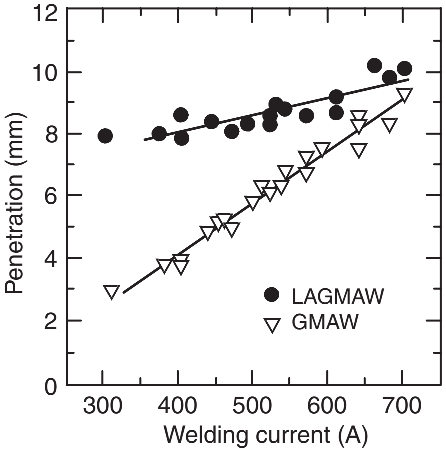

Figure 1.31 Weld penetration in GMAW and laser-assisted GMAW using CO_2 laser at 5.7 kW. Reprinted from Hyatt et al. (24). Courtesy of American Welding Society.

be used for welding dissimilar metals or parts varying greatly in mass and size. Unlike EBW, however, vacuum and x-ray shielding are not required in LBW. However, the very high reflectivity of a laser beam by the metal surface is a major drawback, as already mentioned. Like EBW, the equipment cost is very high, and precise joint fit-up and alignment are required.

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PROBLEMS

1.1 It has been suggested that compared to SMAW, the cooling rate is higher in GMAW and it is, therefore, more likely for heat-affected zone cracking to occur in hardenable steels. What is the main reason for the cooling rate to be higher in GMAW than SMAW?

1.2 The diameter of the electrodes to be used in SMAW depends on factors such as the workpiece thickness, the welding position, and the joint design. Large electrodes, with their corresponding high currents, tend to produce large weld pools. When welding in the overhead or vertical position, do you prefer using larger or smaller electrodes?

1.3 In arc welding, the magnetic field induced by the welding current passing through the electrode and the workpiece can interact with the arc and cause "arc blow." Severe arc blow can cause excessive weld spatter and incomplete fusion. When arc blow is a problem in SMAW, do you expect to minimize it by using DC or AC for welding?

1.4 In the hot-wire GTAW process, shown in Figure P1.4, the tip of the filler metal wire is dipped in the weld pool and the wire itself is resistance heated by means of a second power source between the contact tube of the wire and the workpiece. In the case of steels, the deposition rate can

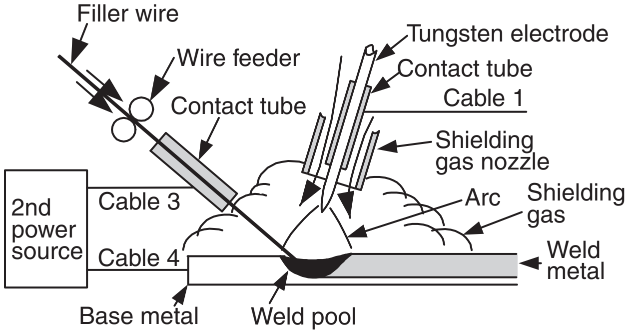

Figure P1.4

be more than doubled this way. Do you prefer using an AC or a DC power source for heating the wire? Do you expect to apply this process to aluminum and copper alloys?

1.5 In GTAW the welding cable is connected to the tungsten electrode through a water-cooled copper contact tube, as shown in Figure 1.11. Why is the tube positioned near the lower end of the electrode instead of the top?

1.6 Measurements of the axial temperature distribution along the GTAW electrode have shown that the temperature drops sharply from the electrode tip toward the contact tube. Why? For instance, with a 2.4-mm-diameter W–ThO_2 electrode at 150 A, the temperature drops from about 3600 K at the tip to about 2000 K at 5 mm above the tip. Under the same condition but with a W–CeO_2 electrode, the temperature drops from about 2700 K at the tip to about 1800 K at 5 mm above the tip (26). Which electrode can carry more current before melting and why?

1.7 Experimental results show that in EBW the penetration depth of the weld decreases as the welding speed increases. Explain why. Under the same power and welding speed, do you expect a much greater penetration depth in aluminum or steel and why?

1.8 How does the working distance in EBW affect the depth–width ratio of the resultant weld?

1.9 Consider EBW in the presence of a gas environment. Under the same power and welding speed, rank and explain the weld penetration for Ar, He, and air. The specific gravities of Ar, He, and air with respect to air are 1.38, 0.137, and 1, respectively, at 1 atm, 0°C.

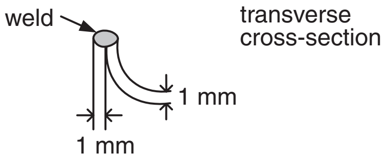

Figure P1.10

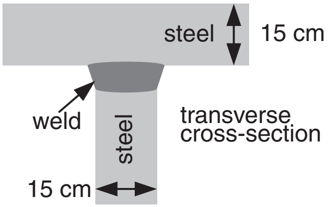

Figure P1.11

1.10 Which arc welding process could have been used for joining the edge weld of thin-gauge steel shown in Figure P1.10 and why?

1.11 Two 15-cm-thick steel plates were joined together in a single pass, as shown in Figure P1.11. Which welding process could have been used and why?