Kirk-Othmer Encyclopedia of Chemical Technology.

WELDING

Welding comprises a group of processes whereby the localized coalescence of materials is achieved through application of heat and/or pressure (1–3). It represents a fabrication technology of extremely broad scope; welding principles are used in nearly every product fabricated, including metals and, increasingly, nonmetals. Obvious examples are bridges, buildings, ships, space vehicles, automobiles, offshore platforms, pipelines, pressure vessels, and consumer appliances; less evident examples include plastic cases for computer disks and the very large number of miniature welds used in microcircuits. This field of great technical complexity utilizes robots, computer-controlled machines, and high concentrations of energy in the form of plasma arcs, lasers, and electron beams. Welding involves very rapid processes, including heat transfer, chemical reactions, and metallurgical reactions, and requires complex methods of analysis to control stress, distortion, and fracture.

The principal welding processes are of comparatively recent origin. Forge welding, soldering, and brazing can be traced to ancient times, but the modern processes of arc welding, resistance welding, and gas welding (as well as thermit welding) were discovered in the 1880s. The use of welding in production and repair increased slowly through the early 1900s and received a boost by successes in emergency ship repair during World War I. Welding saw increased use in building construction during the 1930s, and new welding processes, eg, submerged arc welding, were discovered. World War II provided tremendous impetus for further development, including spectacular uses in all-welded ships and for military tanks and development of new processes for welding aluminum. Since the 1940s many new welding techniques have appeared, including electron-beam, laser, and ultrasonic processes (4).

Thus, from the origins of modern welding in the 1880s many new processes have evolved, and today the American Welding Society recognizes nearly seventy methods of welding and more than twenty allied processes employing thermal cutting, thermal spraying, and adhesive bonding (1), some of which are identified in Table 1.

1. Arc-Welding Processes

In arc welding, the coalescence of metals is achieved through the intense heat of an electric arc, which is established between the base metal and an electrode. The processes listed in Table 1 are differentiated by various means of shielding the arc from the atmosphere (1–3).

In arc processes, either d-c or a-c current is used to establish and maintain an arc between the base metal and an electrode. The electrode itself may be consumed by melting and thus become part of the weld, acting as a filler metal, or it may be a nonconsumable material, eg, tungsten. In the latter case, the heat of the electric arc may simply be used to fuse adjacent base metal (autogenous welding), or a separate filler metal may be added. It is essential that the molten pool of material under the arc, as well as the adjacent solidified but still high temperature metal, be protected from oxygen, nitrogen, and other elements of the atmosphere, since these react with the metal to form oxides and other products that reduce the strength and toughness of a weld. Consequently, various forms of shielding are provided around the arc in the different processes.

Table 1. Welding Processes[a]

Process	Abbreviation	Process	Abbreviation
arc welding		resistance welding	RW
shielded-metal arc welding	SMAW	resistance spot welding	RSW
		resistance seam welding	RSEW
gas–tungsten arc welding	GTAW	projection welding	RPW
		flash welding	FW
plasma arc welding	PAW	solid-state welding	SSW
gas–metal arc welding	GMAW	diffusion welding	DFW
flux-cored arc welding	FCAW	explosion welding	EXW
stud arc welding	SW	forge welding	FOW
submerged arc welding	SAW	friction welding	FRW
oxyfuel–gas welding	OFW	ultrasonic welding	USW
oxyacetylene welding	OAW	other welding processes	
oxyhydrogen welding	OHW	electron beam welding	EBW
pressure-gas welding	PGW	laser beam welding	LBW
brazing	B	electroslag welding	ESW
resistance brazing	RB	thermit welding	TW
furnace brazing	FB	allied processes	
induction brazing	IB	thermal spraying	THS
soldering	S	adhesive bonding	ABD
dip soldering	DS	thermal cutting	TC
wave soldering	WS		
torch soldering	TS		

[a] Ref. 1.

1.1. Shielded-Metal Arc Welding

The essential features of the SMAW process, commonly called stick-electrode welding, are shown in Figure 1**a.** The arc acts between the consumable electrode wire and the base metal, and droplets of molten filler metal are transferred to the weld pool. The unique feature of this widely used process is the role of the electrode coating. This coating is decomposed by the heat of the arc and provides both a necessary shielding atmosphere for the arc as well as a slag coating over the weld metal, thus affording still further protection from the atmosphere.

In addition to these functions, the coating introduces fluxing agents to the weld pool, assists in establishing the electrical characteristics of the arc, and can be used to provide additional filler metal to the weld. Over a dozen different materials may be used in a single electrode covering, depending on the desired welding characteristics. Common ingredients include cellulose and calcium carbonate to provide shielding gas, titanium dioxide and silica to provide slag, sodium silicate to act as a binder, and ferrosilicon to act as a deoxidizer.

Deposition rates using this process are limited by the fact that each electrode contains a finite amount of filler metal. The time required both to change electrodes and to remove the slag coating between each weld pass lowers the overall productivity of the process.

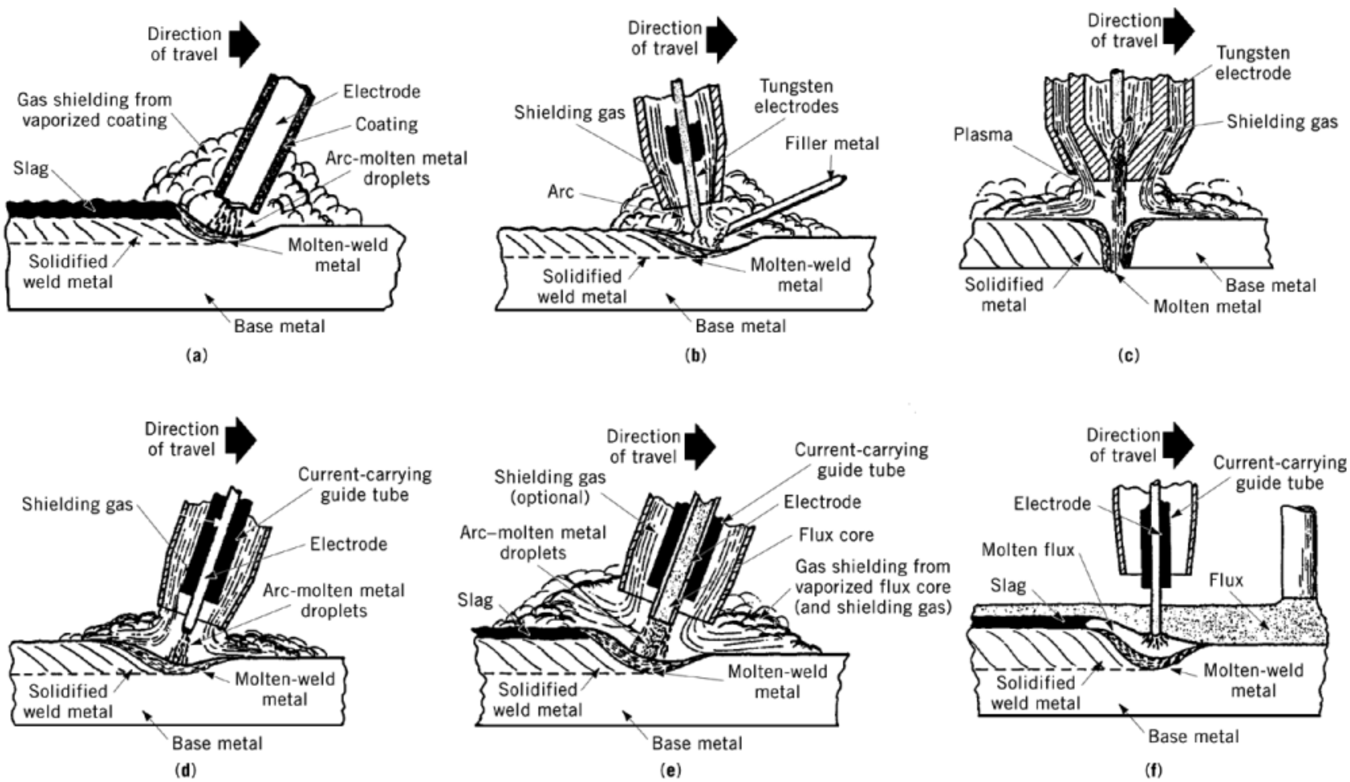

Fig. 1. (**a**) The shielded-metal arc-welding (SMAW) process. (**b**) The gas–tungsten arc-welding (GTAW) process. (**c**) The plasma arc-welding (PAW) process. (**d**) The gas–metal arc-welding (GMAW) process. (**e**) The flux-cored arc-welding (FCAW) process. (**f**) The submerged arc-welding (SAW) process.

1.2. Gas–Tungsten Arc Welding

The GTAW process, often called the tungsten–inert gas or TIG process, is shown in Figure 1**b.** Here the electrode is nonconsumable and shielding is provided by the flow of inert gas through the welding-torch nozzle. Argon and helium are commonly used, as well as argon– helium mixtures; traces of hydrogen are sometimes present. The arc may be used alone to fuse base metal together or, as shown in Figure 1**b,** separately added filler rod can be fed into the weld pool.

1.3. Plasma Arc Welding

In the transferred-arc mode of the PAW process, shown in Figure 1**c,** the arc is between a nonconsumable electrode and the base metal, in a manner similar to the GTAW process. The unique feature is the flow of inert gas around the electrode and through a restricted orifice, which constricts the arc to form a plasma jet. A second, outer stream of shielding gas protects the molten metal from atmospheric contamination. In the nontransferred arc mode of the PAW process, the arc is between the electrode and the constricting orifice. This mode is used for plasma spraying and for heating nonmetals.

1.4. Gas–Metal Arc Welding

The features of the GMAW process, also called the metal–inert gas or MIG process, are shown in Figure **1d.** A consumable bare-wire electrode is fed continuously through the welding torch, and a flow of inert gas through the nozzle provides shielding. This continuous-wire feed leads to higher deposition rates compared to the SMAW process. Common shielding gases include 100% argon, 75–80% argon with the remainder carbon dioxide, and 100% carbon dioxide.

1.5. Flux-Cored Arc Welding

The FCAW process is illustrated in Figure **1e.** The characteristic feature is the hollow, flux-filled, consumable electrode, which is fed continuously through the welding torch. The decomposition of the flux provides both arc shielding and a slag blanket over the weld. In a variation of the process, a shielding gas flows through the welding nozzle to provide additional protection for the arc.

1.6. Submerged-Arc Welding

In the SAW process, shown in Figure **1f**, a loose flux is blanketed over the region of the arc. A consumable, bare-wire electrode is fed continuously through the torch into the weld. The molten- and granular-flux blankets provide the necessary arc shielding and slag cover for the solidified weld. This process, often used with operating currents of over 1000 A, provides the highest deposition rate of all the arc-welding processes. The presence of a loose flux makes vertical and overhead welding impractical with the SAW process.

2. Arc-Welding Systems

The various welding processes result in systems of varying complexity. They include at least the electrode and a device for holding or feeding it, the work piece, the power source, and heavy-duty cabling to provide a complete electrical circuit. Provisions for supply and control of gas and control of wire feed and movement of the electrode assembly are required, depending on process type and degree of automation.

Welding systems are generally classified as manual, semiautomatic, mechanized, and automatic (2). In manual welding, the operator must maintain the arc, feed in filler metal, and provide travel and guidance along the joint. In semiautomatic welding, the welding machine maintains the arc and feeds filler metal, and the operator controls joint travel and provides guidance. In mechanized welding, the welding machine maintains the arc, feeds filler metal, and moves a mounted torch along the joint; the operator manually adjusts the welding parameters based on observation of the process. In automatic welding, the machine assumes all of the preceding functions. Automatic processes may be further classified, depending on the degree of feedback control used in controlling the welding variables. Automated systems may be dedicated to a specific type of production, or they may be flexible, programmable robot systems.

The power source is the core of any welding system. Electrical power is provided by direct-line power or a generator; the latter is driven by an engine or an electric motor. In the case of welding with a-c current, the welding power source may be in the form of a transformer working from line power, or it may be an engine-driven a-c generator. Welding with d-c power may require a transformer–rectifier working from single- or three-phase line current, or a motor-driven generator. Welding power sources are further differentiated by controls imposed on the output current or voltage. One type of power source, used primarily for manual welding, is capable of providing essentially constant current. Another type, used for semiautomatic and automatic processes, is capable of providing essentially constant voltage.

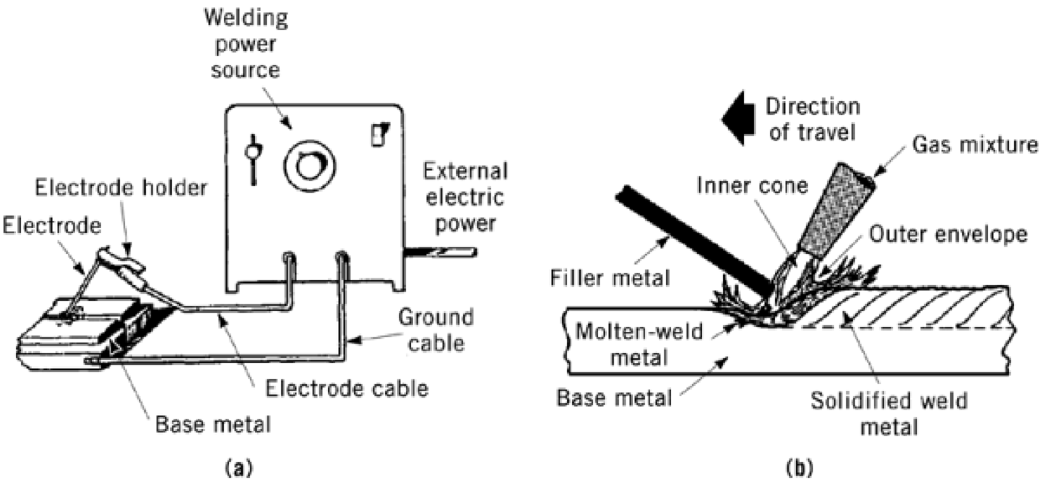

Fig. 2. (**a**) The shielded-metal arc-welding system. (**b**) The oxyacetylene welding process.

The introduction of inverter power sources with solid-state electronic components has resulted in weight and size reductions of up to 75% compared to traditional power supplies. The efficiency and performance of these power supplies is also increased. Variable-frequency, pulsed-current power supplies for GMAW and GTAW, wherein a base current level pulses to high currents, depend on inverter technology. Pulsed GMAW, with pulsing rates of 60 to 200 times per second, provides spray metal transfer at lower average currents and with less fume and spatter; the ability to weld thinner material and to make out-of-position welds is also increased. Pulsed GTAW, with pulsing rates of 1 to 20 times per second, provides greater penetration for a given average current and provides for thin-section welding at lower average currents. High (ca 20 kHz) frequency, pulsed GTAW can be used to provide a stiffer, more directional arc.

The system for shielded-metal arc welding, shown in Figure 2**a,** is the simplest system. It consists of the power source, electrode and holder, the base metal, and the electrical cables or leads. When the arc is struck, a complete electrical circuit is provided. With d-c welding, the electrode may be either negative (straight polarity) or positive (reverse polarity). Shielded metal arc welding is only used manually.

A gas–tungsten arc-welding system is more complex. In addition to the components of the shielded-metal arc system, provisions must be made for the inert gas supply and water or air cooling of the welding torch. GTAW systems may range from manual to automatic.

A semiautomatic flux-cored arc system is shown in Figure 3. Controls and drive motor are required for continuous feed of the welding wire to the torch. If a shielding gas is used, provisions for control of this gas supply are needed, and the torch configuration is different. The flux-cored system may be used for gas–metal arc welding (GMAW) by using the shielding gas and the welding torch configuration for use with gas. Both FCAW and GMAW systems can be used in automatic operations.

A mechanized, submerged-arc-welding system requires a power source, control system, and wire-feed provisions. Granulated flux is fed into the weld joint from a flux hopper, which travels ahead of the welding arc as part of the electrode carriage. Control of the welding torch along the seam of the base metal can be accomplished by a motorized electrode carriage moving along a straight beam, or by a positioner capable of placing the welding torch at any position over a base metal that is itself continually changing position.

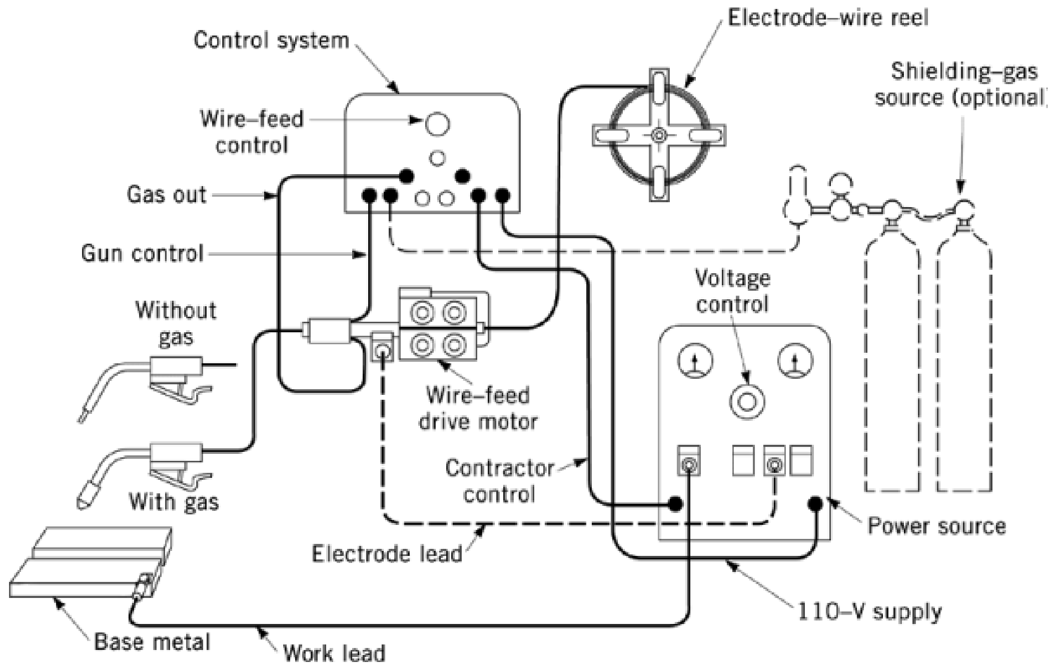

Fig. 3. The flux-cored arc-welding (FCAW) system (2).

3. Other Important Fusion Welding Processes

3.1. Oxyfuel–Gas Welding

This process, commonly called gas welding, uses the heat of combusting gases to melt and coalesce base metals. Although several different fuel gases, eg, propylene, hydrogen, MAPP, or methane, can be added to the oxygen, the oxyacetylene flame is the most widely used because its high (3100°C) flame temperature is needed to weld steel. The essential features of the process are shown in Figure 2**b.** The heat of the inner cone of the flame melts both the base and the filler metal. The overall system is simple; it consists of gas regulators, hoses, the welding torch, a high pressure oxygen tank, and the acetylene tank, which contains liquid acetone into which the acetylene is dissolved. Gas welding, once the most widely used welding method, has been supplanted by arc processes in commercial manufacture. However, it is still used in small welding shops, for repairs, and by the home craftsman.

3.2. Resistance Welding

As noted in Table 1, resistance welding comprises several processes; the most widely used is resistance spot welding (RSW). The principles of RSW are quite different from those underlying the processes previously described (Fig. 4). The workpieces are firmly clamped between copper electrodes, and an electric current is passed through the assembly. Heat is generated by the electrical resistance of the components, the maximum heat occurring at the interface between the workpieces. A nugget of metal at the interface region is melted, at which time the current is shut off and the clamping force on the electrodes released. The entire sequence typically requires less than a second. Resistance spot welding is widely used in the production of thin-gauge, sheet-

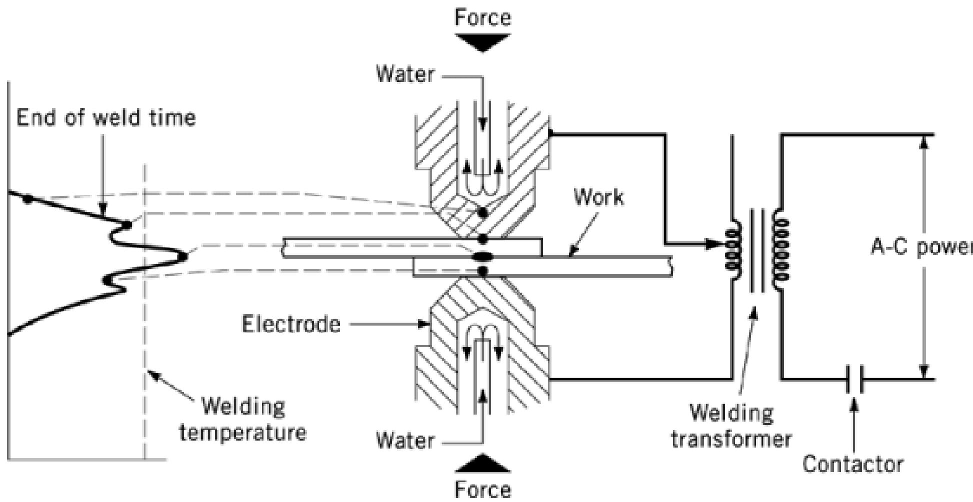

Fig. 4. The resistance spot-welding process (2).

metal assemblies, eg, automobile bodies. It is a high speed production process and is suitable for automation. Although mainly used for welding steel, it is also used with aluminum and other materials (5).

3.3. Electroslag Welding

In this process, the heat of a molten slag coalesces the base and filler metals. Electric current flows from a consumable electrode through a molten metallurgical slag into the molten weld metal. The electric resistance of the slag provides the heat to maintain the slag in a molten state and to melt the weld and base metals. In order to contain the molten metal and slag in the gap between the vertical base-metal plates, water-cooled copper shoes are placed on each side of the gap. The molten metal progressively solidifies upward from the bottom of the pool, welding the plates together in one pass. Although initially an electric arc melts the slag, steady electroslag welding is a nonarc process. It has acquired extensive use in welding thick sections of metal. Deposition rates are very high. It is an automatic process that is generally used in the vertical direction.

3.4. Electron–Beam Welding

This welding process achieves the heat necessary for coalescence by bombarding the base metals with a concentrated stream of electrons. Electrons emitted by a heated filament are accelerated between cathode and anode and then focused into a narrow beam onto the base metal. The kinetic energy of the electrons is converted to heat and x-rays upon impact. The electron beam permits the welding of thick sections, but with a very narrow zone of molten metal. Electron-beam welding is usually performed in a very high or hard vacuum. Modifications have led to soft and out-of-vacuum welding, although penetration capability is sacrificed (6).

3.5. Laser-Beam Welding

The heat of coalescence is produced by focusing the beam of light (photons) from a high power laser on the base metal. Laser welding is considered a high energy–density (ca 10^6 W/cm^2) welding process, with weld characteristics similar to the electron beam. Thus, at low energy, surface melting occurs, but at high energy, a deep penetration of the base metal is possible. Unlike the electron beam, the laser does not require a vacuum and can be used to weld nonconductive materials such as polymers. Because the laser beam is essentially a light beam, it is easily controlled by mirrors, beam splitters, and other optical devices, which leads to great flexibility in its use (6). High reflectivity materials such as aluminum are noted for being more difficult to weld using lasers.

4. Nonfusion Welding Processes

4.1. Solid-State Welding

Solid-state welding comprises a group of welding processes wherein a bond is made between two base materials upon the application of pressure at a temperature below the solidus of the base materials (Table 1). Interlayers are sometimes used. By joining materials in the solid state, many of the difficulties of the fusion processes are avoided.

Friction welding is the most common solid-state process. One type, direct-drive friction welding, is accomplished by spinning one piece rapidly against a second, stationary piece to produce frictional heating. When the metal is at a forging temperature below the solidus, rotation is stopped and axial force is applied. Heated metal, together with oxide and surface contamination, is squeezed out of the interface between the two pieces in the form of a metal flash, which can be trimmed to form a smooth surface.

Geometries that have rotational symmetry on at least one of the parts are particularly suitable for friction welding: round bars and tubes, as well as bar-to-sheet and tube-to-sheet applications. The speed of the process, as well as its ease of automation, promote high volume production. Certain metals are not suitable for friction welding, ie, nonforgeable metals, which tend to crumble under heat and pressure, and free-machining alloys, the inclusion content of which can lead to difficulties as the parts are spun and forged together.

Another variant of the friction welding process, linear friction welding, uses servo-hydraulics pumps to vibrate parts back and forth against each other. Bond areas of approximately 1000 mm^2 can be joined; the attachment of turbine blades to rotors is a prevalent application of this technology.

4.2. Brazing and Soldering

In brazing and soldering processes, a molten filler metal flows by capillary action into the closely fit joint between the base metals at a temperature below the melting point of the base metal. Bonding is accomplished by metal-to-metal adhesion, which may involve the formation of intermetallic compounds at the interface between the base and filler metals. Although these characteristics are common features of brazing and soldering, the two processes are differentiated by the melting temperature of the filler metal. In brazing processes, the filler metal melts at a temperature above 450°C, whereas in soldering, the melting point of the filler metal is below 450°C (7). Common solder alloys contain lead with amounts of tin varying from less than 5 wt % to around 60 wt %; the eutectic composition of 61.9 wt % tin and 38.1 wt % lead melts at 183°C. Common applications for lead–tin solders including plumbing and electronics. Current (ca 1997) efforts to achieve lead-free solders are concentrating on alloys such as tin with 3.5 wt % silver.

Transient liquid-phase bonding is a technique that can form a brazing or soldering joint at low temperature that can withstand service at higher temperature, sometimes approaching the melting temperature of the base metal. A boron-rich brazing filler paste is used for the repair of gas-turbine engine components. Boron acts as a melting-point depressant and allows the paste to melt and fill defects. The small, highly mobile boron atoms rapidly diffuse into the parent metal at brazing temperatures; the remaining filler metal has a melting point that approaches that of the base metal. Transient liquid-phase soldering for tooling and microelectronics assemblies depends on the dissolution of a high melting-point metal into a solder to form an intermetallic compound which has a higher melting point than the original solder.

Wetting, the ability of the filler metal to spread through the joint, is a critical factor in these processes. Any oxides or other film must be cleaned from the joint area, generally by a fluxing agent, to ensure good wetting. Uniform heating of the joint area on large parts may best be accomplished in a furnace. Brazing can be used to join ceramics as well as metals. Metal-to-ceramic brazing is often accomplished with the addition of reactive metal, such as titanium or zirconium, to the braze material.

5. Joining of Polymers and Adhesive Bonding

Polymers are characterized as thermosetting and thermoplastic with respect to the methods by which they are joined. Thermosetting polymers are permanently hard and do not soften upon the application of heat; they are joined by mechanical fasteners and adhesives. Several methods have been devised to join thermoplastic polymers, as well as thermoplastic composite materials, which soften upon heating.

5.1. Hot Plate, Infrared, and Hot Gas Welding

These processes involve external means to heat thermoplastic polymers to a viscous state in which the interdiffusion of polymer chain molecules can occur with the application of pressure. In hot plate welding, the two surfaces to be joined are forced against a platen heated to a desired temperature based on the composition of the polymer. After heating occurs, the platen is removed and the two polymer faces are forged together to make a weld. The platen is replaced as a heat source by infrared light in the infrared welding process; the forging step after heating remains the same. In hot gas welding, a stream of heated gas or air is directed at both the joint surfaces and a polymer filler material. In a process similar to the arc welding of metals, the polymer filler metal is fed into the joint to complete the weld.

5.2. Friction and Ultrasonic Welding

Both rotational and linear friction can be used to melt the interface between two thermoplastics. The parts are then aligned, and a weld is formed as the interface solidifies. Linear friction welding, also called vibration welding, employs frequencies in the 100–500 Hz range; welding can be accomplished in less than one second but is limited to bond areas approximately 400 mm^2. Ultrasonic welding of polymers involves oscillations of 10–50 kHz, which are dissipated at the bond line to produce heat through both friction and hysteresis. The surfaces to be joined are held together as the sound energy generated by the welding machine is transferred through the parts at right angles to the contacting surfaces. Like the friction process, ultrasonic welding is limited to smaller part sizes.

5.3. Adhesive Bonding

As one of the processes allied to welding, adhesive bonding is used particularly in applications where welding or mechanical fastening is either impossible or undesirable (Table 1). Adhesives, which are derived from polymers, are not structural materials and act only to distribute stress over the bond area; as such, proper joint design and minimization of bondline thickness are essential. The selection of an adhesive should take into account the expected service environment, because temperature and atmosphere can degrade adhesives. Stress mode is also a prime consideration in both joint design and adhesive selection. Pure compression, shear, and tension are preferred over mixed stress modes such as peel or cleavage.

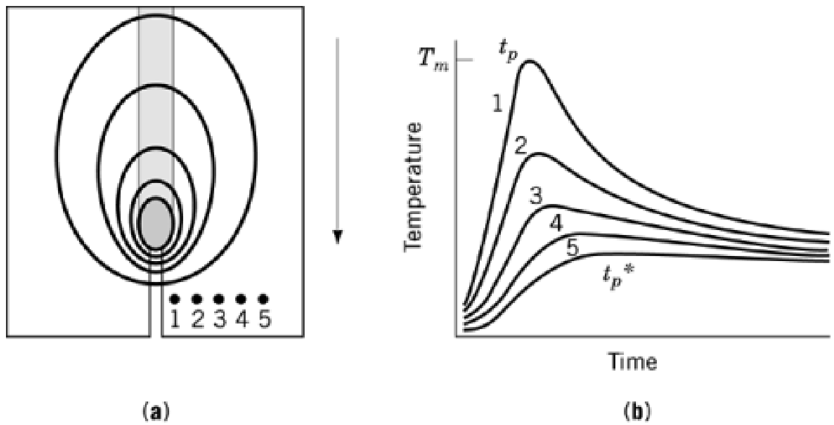

Fig. 5. (**a**) Temperature isotherms in the region of a moving welding arc. (**b**) Heat-affected-zone thermal cycles at various locations in the base plate (see text).

6. Physics and Metallurgy

In most welding processes, the local regions of the adjoining base metals and any added filler metal are melted and resolidified. These features are present, for example, in the arc, gas, electroslag, electron-beam, and laser-welding processes. The analogy of this action to the casting process is often made, where the molten base and filler metals are cast in the mold formed by the nonmolten parts of the base metals. This analogy is of some use because a range of phase transformations is involved as the alloy system solidifies. However, welding differs from conventional casting by the speed of the solidification process. Only a local region of material is melted in welding, and the surrounding, low temperature base metal acts as a large heat sink, producing rapid heat flow from, and the solidification of, the weld zone. This situation produces a complex metallurgical microstructure and physical properties not typical of casting.

6.1. Heat Flow

Certain basic features of welding heat flow are illustrated by Figure 5**a,** which represents isotherms resulting from a welding heat source moving along the joint between two base metals. The central region, under the heat source, is molten. The surrounding elliptical curves are isotherms, which are clustered toward the direction of travel of the heat source and show the temperature distribution at a given instant during welding. Different welding processes, plate thicknesses, and welding speeds modify the details of the clustering and magnitudes of the isotherms, without changing the principles of the behavior shown.

An important aspect of welding heat flow is the thermal cycle at a given location in the material. The nature of the cycle depends on the intensity of the heat source, the speed of welding, the thermal characteristics of the material, and the location in the material. The general behavior is shown in Figure 5**b.** Curve 1, representing point 1 of Figure 5**a,** is adjacent to the weld and actually reaches the melting point, T_{m}, as the arc passes. At points 2–5, two characteristics are evident. First, the peak temperatures that occur, plotted along the line t_{p} to t^*_p, are progressively lower because the heat spreads over larger regions. Second, there is a progressively greater time delay in reaching peak temperature because of the time required for heat conduction. The weld thermal cycle, involving peak temperatures achieved and the speed of heating and cooling, and possibly preheating and postheating, accounts for many of the subsequent complexities of welding metallurgy.

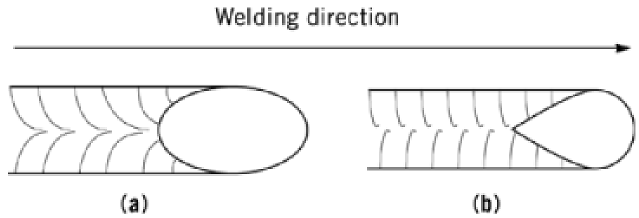

Fig. 6. Weld pool shape and resultant weld–metal solidification direction. (**a**) Slow welding speed. (**b**) Rapid welding speed.

6.2. Solidification

The heat of the electric arc melts a portion of the base metal and any added filler metal. The force of the arc produces localized flows within the weld pools, thus providing a stirring effect, which mixes the filler metal and that portion of the melted base metal into a fairly homogeneous weld metal. There is a very rapid transfer of heat away from the weld to the adjacent, low temperature base metal, and solidification begins nearly instantaneously as the welding heat source moves past a given location.

Solidification begins as atoms of weld metal attach themselves to the solid metal grains at the weld pool edge; this initial growth is epitaxial, ie, the atomic orientation of the base-metal grains continues into the weld pool. Weld metal grain growth continues in the direction of the maximum temperature gradient, which is initially perpendicular to the edge of the weld pool and tends to remain so for fast welding speeds, but which turns toward the arc in a direction parallel to the weld axis for a slower welding speeds (Fig. 6). Cellular and cellular dendritic are the most common weld solidification modes; the mode itself is affected by temperature gradient, speed of solidification, and solute content of the weld metal.

As the weld metal solidifies, impurity elements are rejected into the molten weld pool, eg, sulfur and phosphorus in steel welds (Fig. 7) (8). The final weld metal to solidify, located along the weld centerline at the surface of the weld, has increased levels of these elements, which act to lower the solidification temperature and, in conjunction with the shrinkage stress resulting from solidification, increase the susceptibility of a weld to solidification cracking at the centerline. This increased risk of cracking is particularly true for fast welding speeds, which promote solidification toward the weld centerline and segregate impurities there.

The thermal cycle of the welding and solidification process has caused additional complex effects to occur. Differing peak temperatures reached at different locations from the weld significantly affect the microstructure of the base metal in the region surrounding the weld. This region, know as the heat-affected zone, contains metal in various types of transformations, including grain growth and recrystallization. The most pronounced of these occurs at the fusion boundary, where large grain sizes characteristic of the adjacent weld metal are formed. The effects diminish the farther away from the weld one moves until, at some distance, there is no discernible change in the base metal.

6.3. Metallurgy

Welding metallurgy deals with the interactions of the base and filler metals and the interactions of these materials with various chemicals injected into the weld via gases, electrode coverings, fluxing and slagging agents, and surface contaminants. For example, a number of gas–metal reactions are possible where the weld is still at high temperature. Oxygen, nitrogen, water vapor, and carbon dioxide are gases that react with ferrous metals to yield products harmful to the metallurgical properties of a weld. The nature of the slag–metal reactions that occur in the molten state strongly depends on the composition of the flux or the electrode coating. Flux chemistry may be altered to control removal of specific weld-metal impurities, such as the addition of

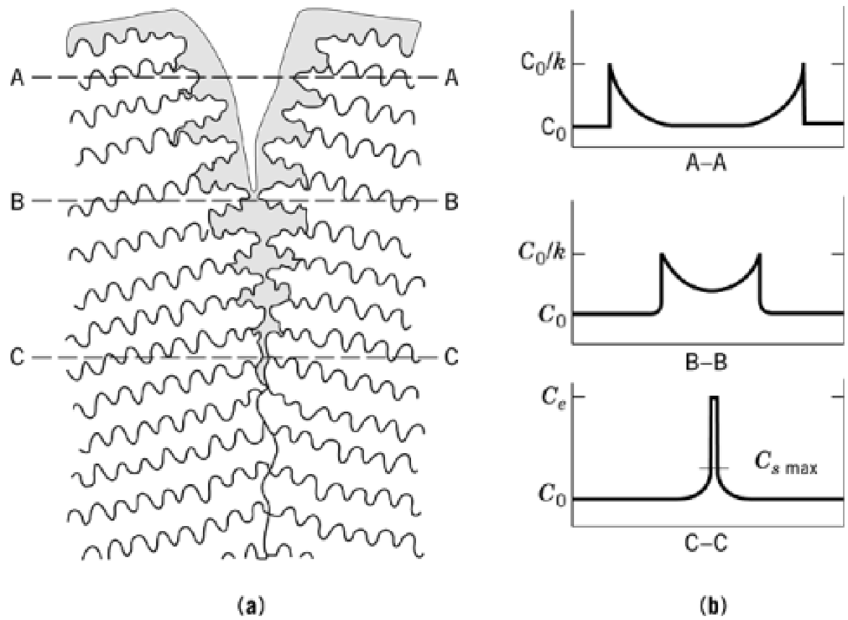

Fig. 7. (**a**) Impurity elements are rejected into the liquid between the dendritic solidification fronts. (**b**) Corresponding impurity concentration profiles. C_0, weld metal composition; k, impurity partitioning coefficient in the liquid; $C_{s\max}$, maximum impurity solid solubility; C_e, eutectic composition at grain boundary.(© NEMJET, The Ohio State University.)

manganese or silicon to provide strong deoxidizing action, or additions to enhance slag removal, with all of these additions influencing the final metallurgical characteristics of the weld.

The microstructure of a weld is the overall arrangement of grains, grain boundaries, and phases that exist once solidification occurs. An important metallurgical tool for understanding weld microstructure is the phase diagram, which, for a given alloy composition, relates material phase and temperature. For example, the iron–carbon, Fe–C, phase diagram shows that a steel of 0.25-wt % carbon melts above 1520°C; at a slightly lower temperature it consists of a mixture of molten metal and delta iron; below 1500°C it is transformed to a mixture of liquid metal and austenite; at 1480°C, it solidifies completely to austenite; and below 815°C, a mixture of austenite and ferrite exists, which is transformed to ferrite and cementite, Fe_3C, at 727°C.

However, phase diagrams represent equilibrium conditions that do not prevail in welding. These nonequilibrium conditions result in changes in the temperatures of phase transformations and in microstructures that have solidified before attaining equilibrium. For example, a very rapid cooling of 0.25-wt % carbon steel results in a martensitic microstructure, a material of greater hardness than is achieved under slow cooling. Cooling rates as well as composition are essential to interpreting the microstructures of deposited weld metal and the surrounding heat-affected zone.

Thus, the metallurgy of welds, comprising the weld metal and surrounding heat-affected zone, is influenced not only by the composition of the materials involved, but also by the welding process, the specific procedures for applying the process, and the heat-transfer characteristics (determined by material, mass, and geometry) of the welded joint (9–12).

6.4. Material Properties

The properties of materials are ultimately determined by the physics of their microstructure. For engineering applications, however, materials are characterized by various macroscopic physical and mechanical properties. Among the former, the thermal properties of materials, including melting temperature, thermal conductivity, specific heat, and coefficient of thermal expansion, are particularly important in welding. The last property named greatly influences structural distortion that can occur in welding. The electrical conductivity of a material is important in any welding process where base or filler metal is part of the welding electrical circuit.

The response of materials to force is characterized by mechanical properties, eg, elastic modulus, yield stress, tensile strength, ductility, hardness, and impact or fracture strength. Fatigue strength, which is the ability of a material to withstand cyclic loading, is of particular importance to welded structures. Welded joints exhibit greatly diminished fatigue strength, compared to unwelded base metal. The various mechanical properties should be known over a temperature range that covers the expected service temperature. The fracture resistance of most materials, for example, is temperature-sensitive.

7. Base and Filler Metals

There is hardly a metal that cannot, or has not, been joined by some welding process. From a practical standpoint, however, the range of alloy systems that may be welded is more restricted. The term *weldability* specifies the capacity of a metal, or combination of metals, to be welded under fabrication conditions into a suitable structure that provides satisfactory service. It is not a precisely defined concept, but encompasses a range of conditions, eg, base- and filler-metal combinations, type of process, procedures, surface conditions, and joint geometries of the base metals (12). A number of tests have been developed to measure weldability. These tests generally are intended to determine the susceptibility of welds to cracking.

7.1. Base Metals

7.1.1. Carbon Steels

In addition to iron, these steels contain only carbon and manganese in appreciable quantities as alloying elements. They are mainly used for structural purposes at ordinary temperatures, eg, beams, columns, and storage tanks. Carbon steels are the most easily welded metals. The heat of welding has a metallurgical effect on the base metal that is in accordance with its composition. It can reduce the strength or corrosion resistance of a metal or otherwise change its properties, but this general effect is lower in carbon steels than in other steels. Steels containing up to 0.30 wt % carbon and 1.00 wt % manganese can be readily welded in thicknesses up to ca 50 mm without special techniques. All welding processes discussed above are used to weld carbon steels.

7.1.2. Low Alloy Steels

These alloys are carbon steels to which other elements have been deliberately added to impart a particular property. Common alloying elements include nickel to improve low temperature mechanical properties; chromium, molybdenum, and vanadium to improve elevated-temperature properties; and silicon to improve properties at ordinary temperatures. Low alloy steels are not used where corrosion is a prime factor and are usually considered separately from stainless steels.

Low allow steels are readily welded but less easily so than plain carbon steels. Alloying additions increase the hardenability of steel, defined as the ability to form the hard, brittle, nonequilibrium-phase martensite upon fast cooling. Hydrogen, which can come from moisture in the welding consumables or grease on the base metal, can cause cracking in steel when martensite is present. As such, low alloy steels are generally preheated to allow hydrogen diffusion out of the weld and to slow down the weld-metal cooling rate to avoid the formation of martensite. In some cases, it may be necessary to subject the welded joint to heat treatment after welding to relieve residual stress and to temper any martensite that may have formed. All of the welding processes previously mentioned may be used for low alloy steels. The filler metal is usually also low alloy steel.

7.1.3. Stainless Steels

Steels containing a minimum of 12 wt % chromium are referred to as stainless steels. They are broadly categorized, based on their steel microstructures, as austenitic, ferritic, and martensitic; other types are precipitation-hardened and duplex (austenite + ferrite) stainless steels. The austenitic chromium–nickel stainless steels are widely used because of their excellent corrosion resistance. There are about twenty different austenitic chromium–nickel steels, which contain varying amounts of chromium and nickel, eg, 18 wt % chromium and 8 wt % nickel is the most common. Upon welding, these steels can undergo a metallurgical change known as carbide precipitation, which reduces the corrosion resistance of the weld and the heat-affected zone. Stabilized stainless steel grades, to which niobium or titanium has been added, and the extra-low carbon grades may be welded without encountering carbide precipitation. Alternatively, the unstabilized grades may be welded and the weldment subjected to a special heat treatment, which dissolves the precipitated carbides and restores the original corrosion resistance. Solidification cracking has also been associated with these steels, particularly where increased sulfur levels are present. The stainless steels are readily welded by all arc welding processes.

Ferritic and martensitic stainless steels may contain up to 27 wt % chromium. Upon welding, ferritic stainless steels are subject to grain growth in the heat-affected zone, together with a subsequent loss in ductility and toughness. Martensitic stainless steels exhibit low as-welded toughness and ductility, and are subject to hydrogen cracking; a post-weld heat treatment is generally required. These steels may be arc welded using carefully planned procedures, including pre- and post-heat treatment. The filler metal is most often a chromium–nickel steel.

The enhanced strength and corrosion properties of duplex stainless steels depend on maintaining equal amounts of the austenite and ferrite phases. The welding thermal cycle can disrupt this balance; therefore, proper weld-parameter and filler metal selection is essential. Precipitation-hardened stainless steels derive their additional strength from alloy precipitates in an austenitic or martensitic stainless steel matrix. To obtain weld properties near those of the base metal, these steels are heat treated after welding.

7.2. Aluminum and Aluminum Alloys

Aluminum alloys are used wherever lightness or atmospheric corrosion resistance are required, or where mildly corrosive fluids are involved. Typical applications for aluminum alloys include railroad tank cars and the skin on aircraft; increasingly, aluminum is being used in the automotive industry. Aluminum alloys are classified as heat-treatable or nonheat-treatable. Strengths of commercially pure and nonheat-treatable alloys are developed by strain hardening and by alloying elements of which magnesium, manganese, and silicon are typical examples. The beneficial effects of strain hardening can be erased by the heat of the welding process; thus, heat inputs are kept low when welding these aluminum alloys. The alloying elements in heat-treatable aluminum alloys are dissolved in the aluminum at high temperature by a process known as solution heat treatment; subsequent heat treatment precipitates these elements as microscopic particles of intermetallic phases, which strengthen the alloy. The welding heat dissolves these particles at or near the weld, thus reducing the strength; properties can be restored by a post-weld heat treatment.

Molten aluminum has an affinity for hydrogen, which results in gas porosity, generally small and well dispersed, as the weld metal solidifies. Elimination of the sources of hydrogen, such as moisture, cleaning fluids, and mill oil, reduces the amounts of porosity. Weld-metal solidification cracking is noted to occur in aluminum alloys that contain significant amounts of copper and magnesium, such as 2024 and 7075; liquation cracking at the heat-affected zone occurs in 6XXX- and 7XXX-series alloys. Aluminum– lithium alloys, the higher elastic modulus and lower density of which have made them of interest to the aerospace industry, have also experienced cracking problems. Gas–metal arc, gas–tungsten arc, and resistance welding are widely used to join aluminum and its alloys.

7.2.1. Magnesium Alloys

In its pure state, magnesium does not have sufficient mechanical strength for structural purposes and must be alloyed with other elements, such as aluminum, zinc, manganese, and zirconium; rare earths and thorium are used for high temperature applications. Magnesium alloys may be divided into room-temperature and elevated-temperature service groups. Certain magnesium alloys are subject to stress corrosion. Weldments subjected to corrosive attack over a period of time may crack adjacent to the weld seams if the residual stresses are not removed. Gas–tungsten arc welding and gas–metal arc welding are recommended for joining magnesium, the former for thinner materials and the latter for thicker materials. Maintaining a protective atmosphere is a critical issue in welding these alloys.

7.2.2. Nickel and Nickel Alloys

This group of metals includes commercially pure nickel and a variety of nickel alloys such as Monel (ca 67% nickel, 30% copper alloys), Inconel (ca 77% nickel, 16% chromium alloys), Incoloy (ca 32% nickel, 21% chromium, 45% iron alloys), and Hastelloy (nickel–molybdenum–iron alloys). Nickel and nickel alloys are used because of their corrosion-resisting properties; the Inconel and Incoloy alloys exhibit good mechanical properties and oxidation resistance at elevated temperatures. Post-weld heat-treatment cracking, also called strain-age cracking, has been associated with heat-treatable nickel alloys. This cracking is particularly pronounced when the combined titanium and aluminum concentration is greater than 5 wt %. Solidification cracking also occurs in these alloys. Nickel alloys can be welded with the shielded-metal arc, submerged-arc, gas–metal arc, or gas–tungsten arc process.

7.2.3. Titanium and Titanium Alloys

Vacuum or inert gas environments are used to weld titanium and its alloys, which have a high affinity for oxygen; commonly used processes are GTAW, PAW, and GMAW, as well as laser and electron-beam welding. Alpha-titanium alloys, which have a hexagonal close-packed atomic structure, have good weldability and are generally welded in the annealed state. Metastable beta-titanium alloys, which have a body-centered-cubic atomic structure, can be welded in the annealed or heat-treated condition. The ductility of welded joints in beta alloys can be low after post-weld aging; therefore these alloys are generally used in the as-welded condition, having good ductility but lower strength. The mechanical properties of alpha + beta titanium alloys can be greatly altered by the welding thermal cycle; weld-metal ductility is generally low. Unalloyed or alpha-titanium filler metal is used to improve ductility in these alloys. T-6Al-4V (6 wt % aluminum, 4 wt % vanadium) has the best weldability among the alpha–beta alloys and accounts for half of industrial titanium usage (3).

7.2.4. Copper and Copper Alloys

The coppers are divided into oxygen-bearing and oxygen-free coppers. Numerous copper alloys are of commercial importance, including those alloys with zinc (brasses), with tin (phosphor bronzes), and with aluminum (aluminum bronzes); all are weldable. In welding copper itself, the copper must be free of oxygen if the joint strength is required to be equal to that of the base metal. Copper alloys and can be welded with the shielded-metal arc, gas–metal arc, and gas–tungsten arc process.

7.2.5. Reactive and Refractory Metals

The reactive and refractory metals, originally used in the aerospace industry, are now welded for many applications. The refractory metals, ie, tungsten, molybdenum, tantalum, and niobium, have extremely high melting points, relatively high density, and high thermal conductivity. The reactive metals, ie, zirconium, titanium, and beryllium, have lower melting points and densities, and, except for zirconium, have higher coefficients of thermal expansion. The metals of both groups are difficult to weld. Their high affinity for oxygen and other gases at elevated temperature excludes those processes that utilize fluxes or those in which heated metal is exposed to the atmosphere. Special care must be taken to maintain a protective atmosphere during welding. Small amounts of impurities cause brittleness. The surfaces must be well prepared and very clean to maintain a contamination-free environment during welding and cooling. Beryllium, because of its toxicity, requires special precautions. Gas–tungsten arc welding may be used for all these metals and gas–metal arc welding for some. Electron-beam and laser welding may also be used.

7.2.6. Filler Metals

Filler metals are added to a weld by melting a consumable electrode or a separate wire fed into the weld pool. In the first category, the filler metal is part of the welding electrical circuit and may be in the form of short lengths of covered wire, as in shielded-metal arc welding, or in the form of continuous reels of wire used in semiautomatic, mechanized, and automatic welding processes. Solid wire is used in the gas–metal and submerged-arc welding processes, whereas a hollow, flux-filled wire is used in flux-cored arc welding. More filler metal in the form of iron powder is sometimes added to the electrode coating or flux. In the second category, the filler metal may be in the form of short lengths of bare solid wire, as used in gas welding or manual gas–tungsten arc welding, or in continuous reel form, used in automatic gas–tungsten arc welding.

Filler metals are manufactured in many special forms for welding the commercial alloy systems described herein. The American Welding Society (AWS) has issued specifications covering the various filler-metal systems and processes (2), eg, AWS A5.28 which applies to low alloy steel filler metals for gas-shielded arc welding. A typical specification covers classification of relevant filler metals, chemical composition, mechanical properties, testing procedures, and matters related to manufacture, eg, packaging, identification, and dimensional tolerances. New specifications are issued occasionally, in addition to ca 30 established specifications. Filler-metal specifications are also issued by the ASME and the Department of Defense (DOD). These specifications are usually similar to the AWS specification, but should be specifically consulted where they apply.

8. Design

8.1. Welded Joints

The weld joint is the geometric arrangement between two pieces of base metal brought together for purposes of welding (13). There are only five recognized weld-joint configurations: corner, butt, tee, lap, and edge joints (Fig. 8). Thus, a butt joint is located between two members in approximately the same plane, whereas a corner joint brings the edges together with an included angle between the planes of the two parts. A tee joints brings the edge of one part onto the planar surface of the second part with a 90° angle between the plates. In a lap joint, one member overlaps another, and an edge joint brings the edges of two parts together without an included angle.

8.2. Weld Types

A weld may be applied to the various joints in different ways, as shown in (Fig. 9). The fillet weld joins corners and tees. In the plug weld, the two pieces are joined by weld metal deposited in a prepared hole in the overlying piece. For a spot weld, heat is applied to the overlying plate, creating fusion at the interface. Resistance welding is generally used for the spot weld and the seam weld. The groove weld joins base metals in a butt joint. For the backing weld, the root of the original weld is first removed by chipping or gouging. Surface welds are used

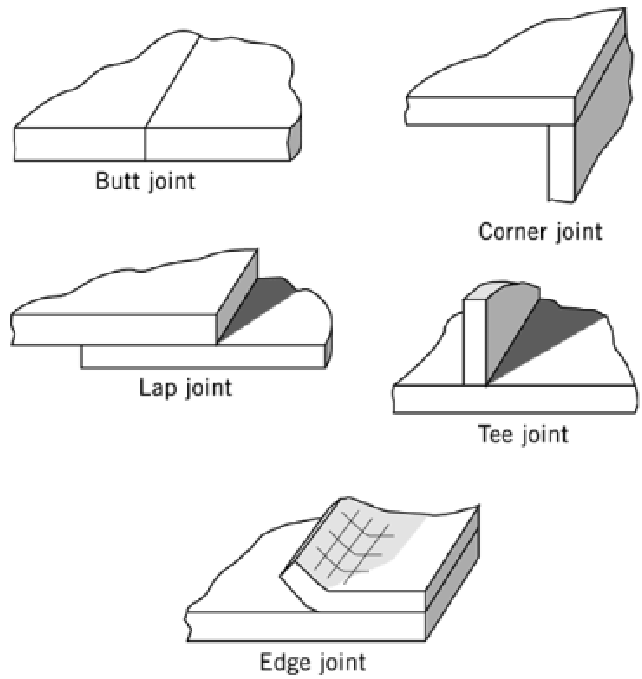

Fig. 8. The five types of welded joints.

to build up the surface of parts with special materials or to replace worn material. Flange welds are applied to edge joints, particularly to thin-section materials.

The edges of the joint to be welded must be prepared. The simplest joint is the square butt joint welded from one or both sides. However, such welds can only be used on thin-gauge material, since it is difficult to penetrate the joint. Various edge penetrations permit fusion across the thickness of the material. Bevel and V grooves are typically prepared by flame cutting, whereas J and U grooves require machining. The selection of single or double grooves is dictated by a variety of practical considerations. Thus, for access to only one side of a surface, a single groove is needed. Double grooves require additional preparation, but their costs are usually offset by a net reduction in weld cross-sectional area, resulting in savings in metal and welding time.

Another design factor is the position in which the weld must be made, which identifies the general orientation of the surface or of the axis of the weld (2). The positions are referred to as flat, horizontal, vertical, and overhead. In the flat position, welding is performed from the upper side of the joint, and the surface is horizontal. In a horizontal weld, the axis is horizontal, but the surface is inclined at an angle. Most processes are applied to the flat position, which is the most convenient and gives the least number of defects. The most difficult position is the overhead position, and those welds are more prone to defects. Manual or semiautomatic processes require higher skill for welding in these positions. Special fixtures and positioning equipment are often used to permit welding in the flat or horizontal position.

8.3. Stress and Distortion

The forces acting on a structure are transmitted through the welded joints; that is, the joint is subjected to simple tension (or compression), bending, shear, or torsional stresses, or to combinations of these stresses owing

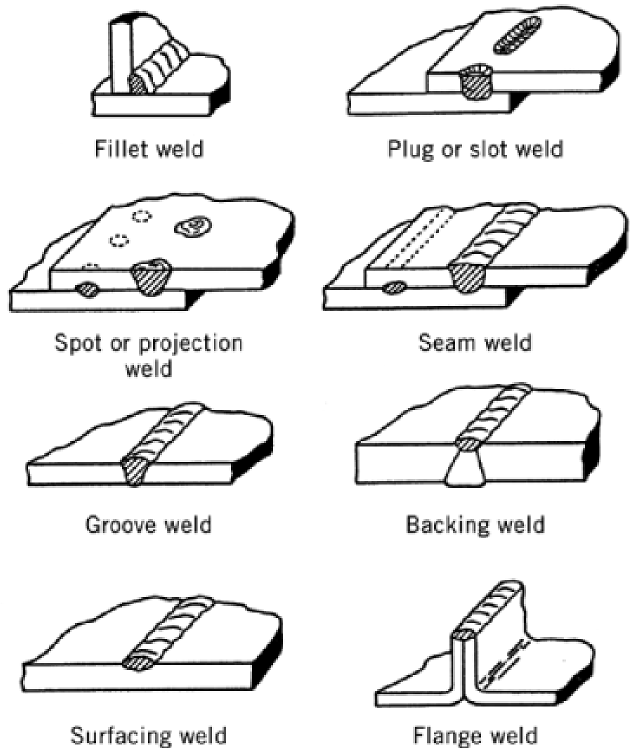

Fig. 9. The eight types of welds.

to combined loading situations. Weldments must be of a proper size, length, and location to withstand the loads imposed during service.

The magnitude and nature of the load are considered in formulating the design. The load may be essentially quasistatic, cyclic, or impact. Many structural failures, for example, have been caused by supposedly innocuous structural details welded in place without any consideration given to their effect on fatigue properties. The service temperatures are also important, since they affect the fracture resistance of a material.

The welding process itself may induce significant stress and distortion, primarily because the molten filler metal is at maximum volume. With cooling and solidification, the material contracts and thereby exerts stresses on the surrounding base metal. Without structural restraint, these stresses cause distortion until they are relieved or minimized. Distortions that occur in simple fillet and butt welds are shown in Figure 10. However, constraint imposed by the surrounding structure may prevent distortion. In this case, significant residual stress may be present, such as tensile stress along the weld axis in a plate. The residual stresses owing to welding may be quite high, approaching or reaching the yield stress of the material. These stresses, in combination with metallurgical considerations, may cause cracking in the weld.

9. Welding Discontinuities

Welding discontinuities are divided into several categories. Fatigue cracks, creep cavities, and failure resulting from overstress are referred to as service-related. Because steel comprises such a large percentage of welded

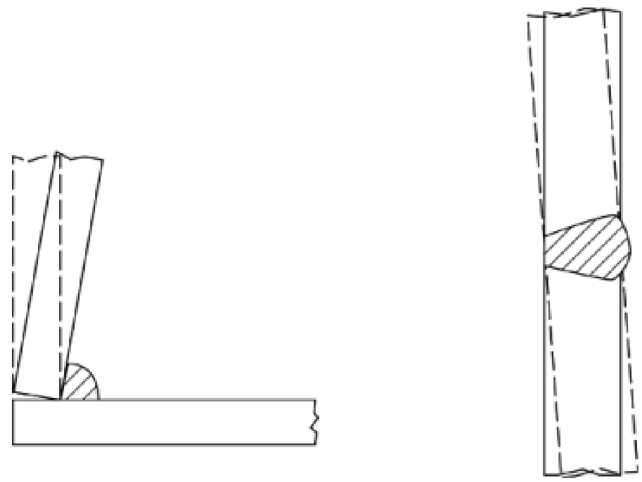

Fig. 10. Weld distortion.

structures, hydrogen-related discontinuities, which are unique to steel, are listed as a separate category. Fabrication discontinuities occur as a result of the welding process and are described herein. Liquid weld metal can dissolve more gas than solid metal; thus, solidifying weld metal evolves gas bubbles, which may become trapped in the solid metal as porosity. Welding processes that employ a flux are subject to trapped slag inclusions if slag is not completely removed between weld passes. Lack of fusion occurs when weld metal does not properly fuse with either the side of the joint or a previous weld pass. Weld spatter consists of small droplets of electrode material that land beside the weld and adhere to the base metal. Undercut results where a groove, melted at the edge of a weld, is not filled with weld metal. Where the size of a discontinuity exceeds the tolerance limits of a specified welding code, the discontinuity is termed a defect and must be removed, eg, by grinding, and rewelded.

10. Testing

The integrity of welded structures depends on the integrity of the welds, and much attention is given to testing methods, such as destructive tests, nondestructive tests, and general weld inspection. An objective of many tests is to determine whether welds contain specific defects, such as porosity, slag inclusions, cracks, or lack of fusion (14, 15).

Destructive tests destroy the specimen or a portion of the production under examination but provide direct information on properties such as tensile strength, impact strength, ductility, and corrosion resistance. Standard destructive tests include determination of the chemical composition of base or weld metal; corrosion-resistance tests; metallographic tests that employ microscopic examination of polished and etched specimens; and hardness tests across the base metal, heat-affected zone, fusion boundary, and weld metal. Mechanical tests include tensile, impact, and guided bend tests. Destructive tests may be used to evaluate the suitability of welding processes or specific welding procedures for a given application. Simple bend or break tests are used for welder qualification. Test requirements are called out in relevant welding and fabrication codes.

Nondestructive evaluation, also termed nondestructive testing or nondestructive inspection, is extensively used in weld testing (14). Nondestructive tests do no impair the serviceability of the material or component under stress. The most widely used tests for evaluation of welds are liquid penetrant, magnetic particle, ultrasonics, and radiography. Acoustic-emission tests are increasingly used. Nondestructive tests detect and characterize, in terms of size, shape, and location, the various types of weld discontinuities that can occur.

Weld inspection duties of personnel responsible for judging the quality of welding with regard to specifications have been treated (15). Some of these duties involve the visual inspection of welds to determine if they are of the proper size, location, and type and are free of defects. Specifications of materials used must be checked, as must equipment and procedures.

11. Economic Aspects

More than 1250 companies are involved in the direct manufacture of products associated with welding, such as power sources, electrodes, and fluxes, as well as a wide range of accessories, eg, protective clothing, positioners, and manipulators (16). An extensive distributor network is involved in sales of these welding products. The Standard Industrial Classification (SIC) system of the United States Government lists 14 welding-related industrial groups (17). A search of the *Thomas Register of American Manufacturers* (18) reveals 2455 companies that offer welding services, ranging from arc and resistance welding to the welding of plastics. *Moody's Industrial Manual* indicates that goods using welding in some stage of fabrication account for at least 30% of the gross national product (19).

The U.S. Bureau of Labor Statistics (20) has listed 416,000 persons employed as welders, cutters, and welding machine operators, with 90% employed in the fields of manufacturing, services, construction, and wholesale trades. The same report projects a decline in employment for welders; job prospects remain good, however, as the number of qualified workers entering the market is expected to balance workers leaving the field.

12. Health and Safety Factors

Welding is carried out in a wide range of industrial environments, such as field construction sites, factory production floors, and small shops. Welders, therefore are subject to the same hazards as all other workers in the metalworking trades. Specific additional hazards of welding include electrical shock, arc radiation, fumes and gases, fires and explosions, compressed gases, cutting and chipping operations, and high noise levels. Many of these hazards also involve workers who share the welding environment. The American National Standards Institute publishes ANSI Standard Z49.1, which covers safe practices for welding and cutting operations (21).

Fumes and gases associated with welding continue to be an area of concern (22–24). Fumes emanate from a number of sources, including electrodes, wires, base metals, coatings and contaminants, ozone produced by the ultraviolet radiation from the welding arc, and gases produced from the heat of the arc. These fumes may lead to a number of health problems, which include acute poisoning under severe cases of ozone and nitrogen oxide concentration, chronic respiratory disease; a condition known as metal-fume fever involving zinc-containing fumes; skin disorders; and disorders of the nervous system, which can be caused by lead or manganese present in welding fumes. A detailed treatment of health and safety in the welding field is found in Reference 25.

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RANDY J. BOWERS
KARL F. GRAFF
Edison Welding Institute

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