CHAPTER 26
WELDED CONNECTIONS

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26.1 DEFINITIONS AND TERMINOLOGY

Arc welding is one of several fusion processes for joining metals. By the application of intense heat, metal at the joint between two parts is melted and caused to intermix—directly or, more commonly, with an intermediate molten filler metal. Upon cooling and solidification, a metallurgical bond results. Since the joining is by intermixture of the substance of one part with the substance of the other part, with or without an intermediate of like substance, the final weldment has the potential for exhibiting at the joint the same strength properties as the metal of the parts. This is in sharp contrast to nonfusion processes of joining—such as soldering, brazing, or adhesive bonding—in which the mechanical and physical properties of the base materials cannot be duplicated at the joint.

In arc welding, the intense heat needed to melt metal is produced by an electric arc. The arc is formed between the work to be welded and an electrode that is manually or mechanically moved along the joint (or the work may be moved under a stationary electrode). The electrode may be a carbon or tungsten rod, the sole purpose of which is to carry the current and sustain the electric arc between its tip and the workpiece. Or it may be a specially prepared rod or wire that not only conducts the current and sustains the arc, but also melts and supplies filler metal to the joint. If the electrode is a carbon or tungsten rod and the joint requires added metal for fill, that metal is supplied by a separately applied filler-metal rod or wire. Most welding in the manufacture of steel products where filler metal is required, however, is accomplished with the second type of electrode—the type that supplies filler metal as well as providing the conductor for carrying electric current.

26.2 BASIC WELDING CIRCUIT

The basic arc-welding circuit is illustrated in Fig. 26.1. An ac or dc power source fitted with whatever controls may be needed is connected by a ground-work cable to the workpiece and by a "hot" cable to an electrode holder of some type, which makes electrical contact with the welding electrode. When the circuit is energized and the electrode tip is touched to the grounded workpiece and then withdrawn and held close to the spot of contact, an arc is created across the gap. The arc produces a temperature of about 6500°F at the tip of the electrode, a temperature more than adequate for melting most metals. The heat produced melts the base metal in the vicinity of the arc and any filler metal supplied by the electrode or by a separately introduced rod or wire. A common pool of molten metal is produced, called a *crater.* This crater solidifies behind the electrode as it is moved along the joint being welded. The result is a fusion bond and the metallurgical unification of the workpieces.

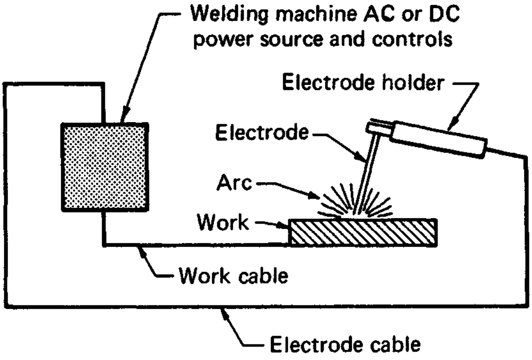

FIGURE 26.1 The basic arc-welding circuit. *(The Lincoln Electric Company.)*

26.3 ARC SHIELDING

Using the heat of an electric arc to join metals, however, requires more than the moving of the electrode with respect to the weld joint. Metals at high temperatures are chemically reactive with the main constituents of air—oxygen and nitrogen. Should the metal in the molten pool come in contact with air, oxides and nitrides would be formed, which upon solidification of the molten pool would destroy the strength properties of the weld joint. For this reason, the various arc-welding processes provide some means for covering the arc and the molten pool with a protective shield of gas, vapor, or slag. This is referred to as *arc shielding,* and such shielding may be accomplished by various techniques, such as the use of a vapor-generating covering on filler-metal-type electrodes, the covering of the arc and molten pool with a separately applied inert gas or a granular flux, or the use of materials within the cores of tubular electrodes that generate shielding vapors.

Whatever the shielding method, the intent is to provide a blanket of gas, vapor, or slag that prevents or minimizes contact of the molten metal with air. The shielding method also affects the stability and other characteristics of the arc. When the shielding is produced by an electrode covering, by electrode core substances, or by separately applied granular flux, a fluxing or metal-improving function is usually also provided. Thus the core materials in a flux-core electrode may perform a deoxidizing function as well as a shielding function, and in submerged-arc welding, the granular flux applied to the joint ahead of the arc may add alloying elements to the molten pool as well as shielding it and the arc.

Figure 26.2 illustrates the shielding of the welding arc and molten pool with a covered "stick" electrode—the type of electrode used in most manual arc welding. The extruded covering on the filler metal rod, under the heat of the arc, generates a gaseous shield that prevents air from coming in contact with the molten metal. It also supplies ingredients that react with deleterious substances on the metals, such as oxides and salts, and ties these substances up chemically in a slag that, being lighter than the weld metal, rises to the top of the pool and crusts over the newly solidified metal. This slag, even after soldification, has a protective function: It minimizes contact of the very hot solidified metal with air until the temperature lowers to a point where reaction of the metal with air is lessened.

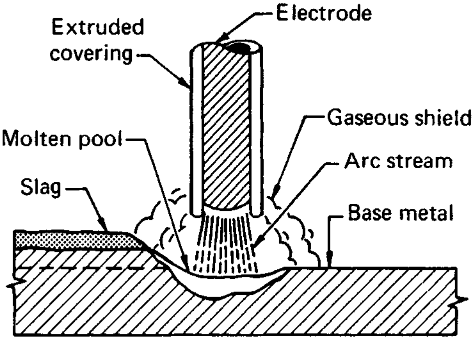

FIGURE 26.2 How the arc and molten pool are shielded by a gaseous blanket developed by the vaporization and chemical breakdown of the extruded covering on the electrode in stick-electrode welding. Fluxing material in the electrode covering reacts with unwanted substances in the molten pool, tying them up chemically and forming a slag that crusts over the hot solidified metal. The slag, in turn, protects the hot metal from reaction with the air while it is cooling. *(The Lincoln Electric Company.)*

While the main function of the arc is to supply heat, it has other functions that are important to the success of arc-welding processes. It can be adjusted or controlled to transfer molten metal from the electrode to the work, to remove surface films, and to bring about complex gas-slag-metal reactions and various metallurgical changes.

26.4 NATURE OF THE ARC

An arc is an electric current flowing between two electrodes through an ionized column of gas called a *plasma.* The space between the two electrodes—or, in arc welding, the space between the electrode and the work—can be divided into three areas of heat generation: the *cathode,* the *anode,* and the arc *plasma.*

The welding arc is characterized as a high-current, low-voltage arc that requires a high concentration of electrons to carry the current. Negative electrons are emitted from the cathode and flow—along with the negative ions of the plasma—to the positive anode, as shown in Fig. 26.3. Positive ions flow in the reverse direction. A *negative ion* is an atom that has picked up one or more electrons beyond the number needed to balance the positive charge on its nucleus—thus the negative charge. A *positive ion* is an atom that has lost one or more electrons—thus the positive charge. However, just as in a solid conductor, the principal flow of current in the arc is by electron travel.

Heat is generated in the cathode area mostly by the positive ions striking the surface of the cathode. Heat at the anode is generated mostly by electrons. These have been accelerated as they pass through the plasma by the arc voltage, and they give up their energy as heat when striking the anode.

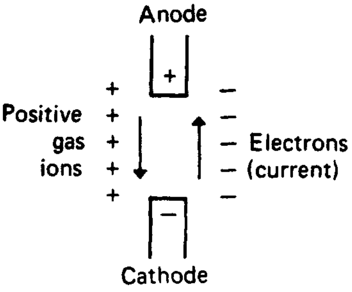

FIGURE 26.3 Characteristics of the arc. *(The Lincoln Electric Company.)*

The plasma, or arc column, is a mixture of neutral and excited gas atoms. In the central column of the plasma, electrons, atoms, and ions are in accelerated motion and are constantly colliding. The hottest part of the plasma is the central column, where the motion is most intense. The outer portion or the arc flame is somewhat cooler and consists of recombining gas molecules that were disassociated in the central column.

The distribution of heat or voltage drop in the three heat zones can be changed. Changing the arc length has the greatest effect on the arc plasma. Changing the shielding gas can change the heat balance between the anode and cathode. The addition of potassium salts to the plasma reduces the arc voltage because of increased ionization.

In welding, not only does the arc provide the heat needed to melt the electrode and the base metal, but under certain conditions it must also supply the means to transport the molten metal from the tip of the electrode to the work. Several mechanisms for metal transfer exist. In one, the molten drop of metal touches the molten metal in the crater, and transfer is by surface tension. In another, the drop is ejected from the molten metal at the electrode tip by an electric pinch. It is ejected at high speed and retains this speed unless slowed by gravitational forces. It may be accelerated by the plasma, as in the case of a pinched-plasma arc. These forces are the ones that transfer the molten metal in overhead welding. In flat welding, gravity is also a significant force in metal transfer.

If the electrode is consumable, the tip melts under the heat of the arc, and molten droplets are detached and transported to the work through the arc column. Any arc-welding system in which the electrode is melted off to become part of the weld is described as *metal arc.* If the electrode is refractory—carbon or tungsten—there are no molten droplets to be forced across the gap and onto the work. Filler metal is melted into the joint from a separate rod or wire.

More of the heat developed by the arc ends up in the weld pool with consumable electrodes than with nonconsumable electrodes, with the result that higher thermal efficiencies and narrower heat-affected zones are obtained. Typical thermal efficiencies for metal-arc welding are in the 75 to 80 percent range; for welding with nonconsumable electrodes, efficiencies are 50 to 60 percent.

Since there must be an ionized path to conduct electricity across a gap, the mere switching on of the welding current with a cold electrode poised over the work will not start the arc. The arc must first be *ignited.* This is accomplished either by supplying an initial voltage high enough to cause a discharge or by touching the electrode to the work and then withdrawing it as the contact area becomes heated. High-frequency spark discharges are frequently used for igniting gas-shielded arcs, but the most common method of striking an arc is the touch-and-withdraw method.

Arc welding may be done with either alternating or direct current and with the electrode either positive or negative. The choice of current and polarity depends on the process, the type of electrode, the arc atmosphere, and the metal being welded. Whatever the current, it must be controlled to satisfy the variables—amperage and voltage—which are specified by the welding procedures.

26.5 OVERCOMING CURRENT LIMITATIONS

The objective in commercial welding is to get the job done as fast as possible so as to lessen the time costs of skilled workers. One way to speed the welding process is to raise the current—use a higher amperage—since the faster electrical energy can be induced in the weld joint, the faster will be the welding rate.

With manual stick-electrode welding, however, there is a practical limit to the current. The covered electrodes are from 9 to 18 in long, and if the current is raised too high, electrical resistance heating within the unused length of electrode will become so great that the covering overheats and "breaks down"—the covering ingredients react with each other or oxidize and do not function properly at the arc. Also, the hot core wire increases the melt-off rate and the arc characteristics change. The mechanics of stick-electrode welding are such that electric contact with the electrode cannot be made immediately above the arc—a technique that would circumvent much of the resistance heating.

Not until semiautomatic guns and automatic welding heads (which are fed by continuous electrode wires) were developed was there a way of solving the resistance-heating problem and thus making feasible the use of high currents to speed the welding process. In such guns and heads, electric contact with the electrode is made close to the arc. The length between the tip of the electrode and the point of electric contact is then inadequate for enough resistance heating to take place to overheat the electrode in advance of the arc, even with currents two or three times those usable with stick-electrode welding.

This solving of the point-of-contact problem and circumventing of the effects of resistance heating in the electrode constituted a breakthrough that substantially lowered welding costs and increased the use of arc welding in industrial metals joining. In fact, through the ingenuity of welding equipment manufacturers, the resistance-heating effect has been put to work constructively in a technique known as long-stickout welding. Here, the length of electrode between the point of electric contact in the welding gun or head and the arc is adjusted so that resistance heating almost—but not quite—overheats the protruding electrode. Thus when a point on the electrode reaches the arc, the metal at that point is about ready to melt and less arc heat is required to melt it. Because of this, still higher welding speeds are possible.

26.6 COMMERCIAL ARC-WELDING PROCESSES

26.6.1 Shielded Metal-Arc Welding

The *shielded metal-arc process*—commonly called *stick-electrode welding* or *manual welding*—is the most widely used of the various arc-welding processes. It is characterized by application versatility and flexibility and relative simplicity in equipment. It is the process used by the small welding shop, by the home mechanic, and by the farmer for repair of equipment; it is also a process having extensive application in industrial fabrication, structural steel erection, weldment manufacture, and other commercial metals joining. Arc welding, to persons only casually acquainted with welding, usually means shielded metal-arc welding.

With this process, an electric arc is struck between the electrically grounded work and a 9- to 18-in length of covered metal rod—the electrode. The electrode is clamped in an electrode holder, which is joined by a cable to the power source. The welder grips the insulated handle of the electrode holder and maneuvers the tip of the electrode with respect to the weld joint. When the welder touches the tip of the electrode against the work and then withdraws it to establish the arc, the welding circuit is completed. The heat of the arc melts base metal in the immediate area, the electrode's metal core, and any metal particles that may be in the electrode's covering. It also melts, vaporizes, or breaks down chemically nonmetallic substances incorporated in the covering for arc-shielding, metal-protection, or metal-conditioning purposes. The mixing of molten base metal and filler metal from the electrode provides the coalescence required to effect joining (see Fig. 26.2).

As welding progresses, the covered rod becomes shorter and shorter. Finally, the welding must be stopped to remove the stub and replace it with a new electrode. This periodic changing of electrodes is one of the major disadvantages of the process in production welding. It decreases the *operating factor*, or the percent of the welder's time spent in the actual laying of weld beads.

Another disadvantage of shielded metal-arc welding is the limitation placed on the current that can be used. High amperages, such as those used with semiautomatic guns or automatic welding heads, are impractical because of the long (and varying) length of electrode between the arc and the point of electric contact in the jaws of the electrode holder. The welding current is limited by the resistance heating of the electrode. The electrode temperature must not exceed the *breakdown temperature* of the covering. If the temperature is too high, the covering chemicals react with each other or with air and therefore do not function properly at the arc.

The versatility of the process—plus the simplicity of equipment—is viewed by many users whose work would permit some degree of mechanized welding as overriding its inherent disadvantages. This point of view was formerly well taken, but now that semiautomatic self-shielded flux-cored arc welding has been developed to a similar (or even superior) degree of versatility and flexibility, there is less justification for adhering to stick-electrode welding in steel fabrication and erection wherever substantial amounts of weld metals must be placed.

26.6.2 Self-Shielded Flux-Cored Welding

The self-shielded flux-cored arc-welding process is an outgrowth of shielded metal-arc welding. The versatility and maneuverability of stick electrodes in manual welding stimulated efforts to mechanize the shielded metal-arc process. The thought was that if some way could be found to put an electrode with self-shielding characteristics in coil form and to feed it mechanically to the arc, welding time lost in changing electrodes and the material lost as electrode stubs would be eliminated. The result of these efforts was the development of the semiautomatic and full-automatic processes for welding with continuous flux-cored tubular electrode "wires." Such fabricated wires (Fig. 26.4) contain in their cores the ingredients for fluxing and deoxidizing molten metal and for generating shielding gases and vapors and slag coverings.

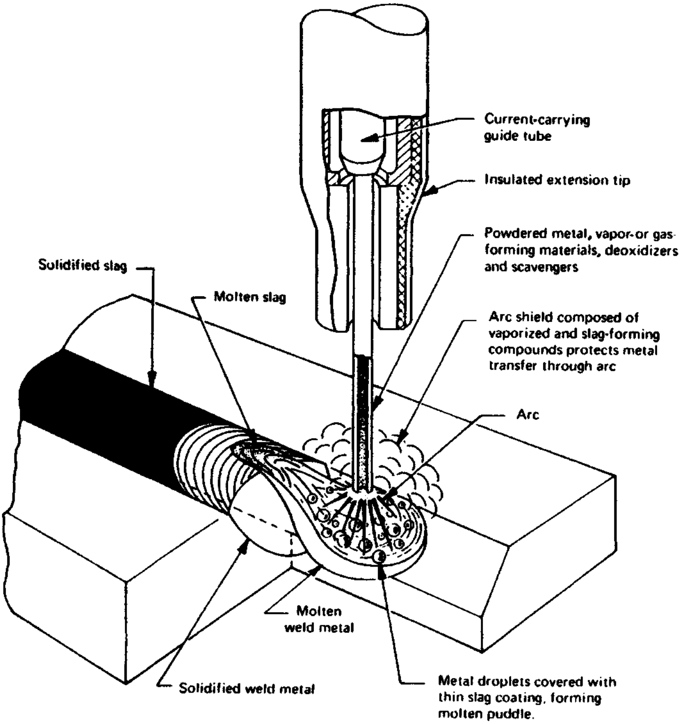

FIGURE 26.4 Principles of the self-shielded flux-cored arc-welding process. The electrode may be viewed as an *inside-out* construction of the stick electrode used in shielded metal-arc welding. Putting the shield-generating materials inside the electrode allows the coiling of long, continuous lengths of electrode and gives an outside conductive sheath for carrying the welding current from a point close to the arc. *(The Lincoln Electric Company.)*

In essence, semiautomatic welding with flux-cored electrodes is manual shielded metal-arc welding with an electrode many feet long instead of just a few inches long.

By pressing the trigger that completes the welding circuit, the operator activates the mechanism that feeds the electrode to the arc. The operator uses a gun instead of an electrode holder, but it is similarly light in weight and easy to maneuver. The only other major difference is that the weld metal of the electrode surrounds the shielding and fluxing chemicals rather than being surrounded by them.

Full-automatic welding with self-shielded flux-cored electrodes goes one step further in mechanization—the removal of direct manual manipulation in the utilization of the open-arc process.

One of the advantages of the self-shielded flux-cored arc-welding process is the high deposition rates that are made possible with the hand-held semiautomatic gun. Higher deposition rates, plus automatic electrode feed and elimination of lost time for changing electrodes, have resulted in substantial production economies wherever the semiautomatic process has been used to replace stick-electrode welding. Decreases in welding costs as great as 50 percent have been common, and in some production welding, deposition rates have been increased as much as 400 percent.

Another advantage of the process is its tolerance of poor fitup, which in shops often reduces rework and repair without affecting final product quality. The tolerance of the semiautomatic process for poor fitup has expanded the use of tubular steel members in structures by making possible sound connections where perfect fitup would be too difficult or costly to achieve.

26.6.3 Gas Metal-Arc Welding

Gas metal-arc welding, popularly known as *MIG welding,* uses a continuous electrode for filler metal and an externally supplied gas or gas mixture for shielding. The shielding gas—helium, argon, carbon dioxide, or mixtures thereof—protects the molten metal from reacting with constituents of the atmosphere. Although the gas shield is effective in shielding the molten metal from the air, deoxidizers are usually added as alloys in the electrode. Sometimes light coatings are applied to the electrode for arc stabilizing or other purposes. Lubricating films may also be applied to increase the electrode feeding efficiency in semiautomatic welding equipment. Reactive gases may be included in the gas mixture for arc-conditioning functions. Figure 26.5 illustrates the method by which shielding gas and continuous electrode are supplied to the welding arc.

MIG welding may be used with all the major commercial metals, including carbon, alloy, and stainless steels and aluminum, magnesium, copper, iron, titanium, and zirconium. It is a preferred process for the welding of aluminum, magnesium, copper, and many of the alloys of these reactive metals. Most of the irons and steels can be satisfactorily joined by MIG welding, including the carbon-free irons, the low-carbon and low-alloy steels, the high-strength quenched and tempered steels, the chromium irons and steels, the high-nickel steels, and some of the so-called superalloy steels. With these various materials, the welding techniques and procedures may vary widely. Thus carbon dioxide or argon-oxygen mixtures are suitable for arc shielding when welding the low-carbon and low-alloy steels, whereas pure inert gas may be essential when welding highly alloyed steels. Copper and many of its alloys and the stainless steels are successfully welded by this process.

Welding is either semiautomatic, using a hand-held gun to which electrode is fed automatically, or done with fully automatic equipment. The welding guns or heads are similar to those used with gas-shielded flux-cored welding.

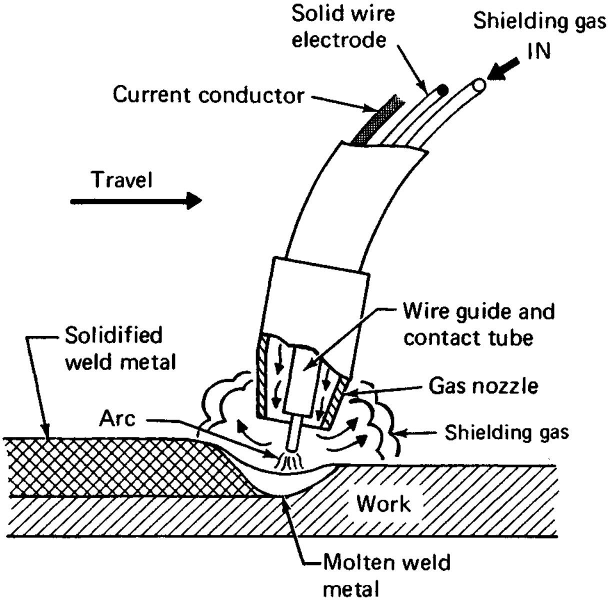

FIGURE 26.5 Principle of the gas metal-arc process. Continuous solid-wire electrode is fed to the gas-shielded arc. *(The Lincoln Electric Company.)*

26.6.4 The Gas-Shielded Flux-Cored Process

The *gas-shielded flux-cored process* may be looked on as a hybrid between self-shielded flux-cored arc welding and gas metal-arc welding. Tubular electrode wire is used (Fig. 26.6), as in the self-shielded process, but the ingredients in its core are for fluxing, deoxidizing, scavenging, and sometimes alloying additions rather than for these functions plus the generation of protective vapors. In this respect, the process has similarities to the self-shielded flux-cored electrode process, and the tubular electrodes used are classified by the American Welding Society (AWS) along with electrodes used in the self-shielded process. However, the process is similar to gas metal-arc welding in that a gas is separately applied to act as arc shield.

The gas-shielded flux-cored process is used for welding mild and low-alloy steels. It gives high deposition rates, high deposition efficiencies, and high operating factors. Radiographic-quality welds are easily produced, and the weld metal with mild and low-alloy steels has good ductility and toughness. The process is adaptable to a wide variety of joints and has the capability for all-position welding.

26.6.5 Gas Tungsten-Arc Welding

The AWS definition of *gas tungsten-arc* (TIG) welding is "an arc-welding process wherein coalescence is produced by heating with an arc between a tungsten electrode and the work." A filler metal may or may not be used. Shielding is obtained with a gas or a gas mixture.

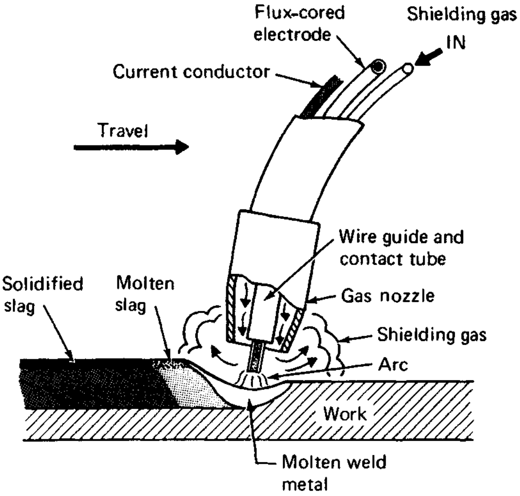

FIGURE 26.6 Principles of the gas-shielded flux-cored process. Gas from an external source is used for the shielding; the core ingredients are for fluxing and metal-conditioning purposes. *(The Lincoln Electric Company.)*

Essentially, the nonconsumable tungsten electrode is a *torch*—a heating device. Under the protective gas shield, metals to be joined may be heated above their melting points so that material from one part coalesces with material from the other part. Upon solidification of the molten area, unification occurs. Pressure may be used when the edges to be joined are approaching the molten state to assist coalescence. Welding in this manner requires no filler metal.

If the work is too heavy for the mere fusing of abutting edges, and if groove joints or reinforcements such as fillets are required, filler metal must be added. This is supplied by a filler rod that is manually or mechanically fed into the weld puddle. Both the tip of the nonconsumable tungsten electrode and the tip of the filler rod are kept under the protective gas shield as welding progresses.

Figure 26.7 illustrates the TIG torch. In automatic welding, filler wire is fed mechanically through a guide into the weld puddle. When running heavy joints manually, a variation in the mode of feeding is to lay or press the filler rod in or along the joint and melt it along with the joint edges. All the standard types of joints can be welded with the TIG process and filler metal.

Materials weldable by the TIG process are most grades of carbon, alloy, and stainless steels; aluminum and most of its alloys; magnesium and most of its alloys; copper and various brasses and bronzes; high-temperature alloys of various types; numerous hard-surfacing alloys; and such metals as titanium, zirconium, gold, and silver. The process is especially adapted for welding thin materials where the requirements for quality and finish are exacting. It is one of the few processes that is satisfactory for welding such tiny and thin-walled objects as transistor cases, instrument diaphragms, and delicate expansion bellows.

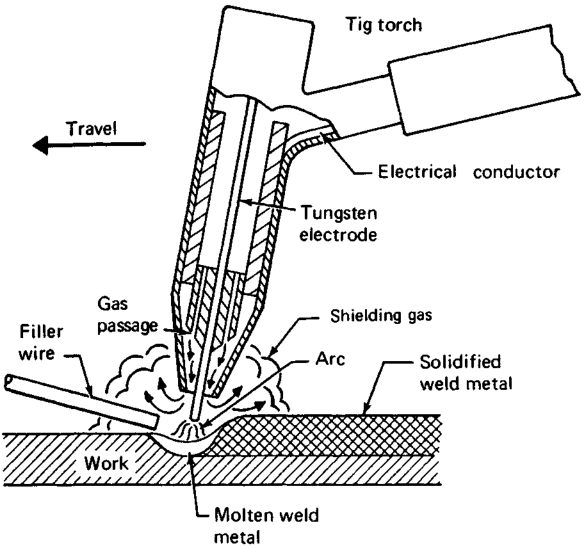

FIGURE 26.7 Principles of the gas tungsten-arc process. If filler metal is required, it is fed into the pool from a separate filler rod. *(The Lincoln Electric Company.)*

26.6.6 Submerged-Arc Welding

Submerged-arc welding differs from other arc-welding processes in that a blanket of fusible granular material—commonly called *flux*—is used for shielding the arc and the molten metal. The arc is struck between the workpiece and a bare wire electrode, the tip of which is submerged in the flux. Since the arc is completely covered by the flux, it is not visible, and the weld is run without the flash, spatter, and sparks that characterize the open-arc process. The nature of the flux is such that very little smoke or visible fumes are developed.

The process is either semiautomatic or fully automatic, and the electrode is fed mechanically to the welding gun, head, or heads. In semiautomatic welding, the welder moves the gun, usually equipped with a flux-feeding device, along the joint. Flux feed may be by gravity flow through a nozzle concentric with the electrode from a small hopper atop the gun, or it may be through a concentric nozzle tube connected to an air-pressurized flux tank. Flux may also be applied in advance of the welding operation or ahead of the arc from a hopper run along the joint. In fully automatic submerged-arc welding, flux is fed continuously to the joint ahead of or concentric with the arc, and fully automatic installations are commonly equipped with vacuum systems to pick up the unfused flux left by the welding head or heads for cleaning and reuse.

During welding, the heat of the arc melts some of the flux along with the tip of the electrode, as illustrated in Fig. 26.8. The tip of the electrode and the welding zone are always surrounded and shielded by molten flux, surmounted by a layer of unfused flux. The electrode is held a short distance above the workpiece. As the electrode progresses along the joint, the lighter molten flux rises above the molten metal in the form of a slag. The weld metal, having a higher melting (freezing) point, solidifies while the slag above it is still molten. The slag then freezes over the newly solidified weld metal, continuing to protect the metal from contamination while it is very hot and reactive with atmospheric oxygen and nitrogen. Upon cooling and removal of any unmelted flux for reuse, the slag is readily peeled from the weld.

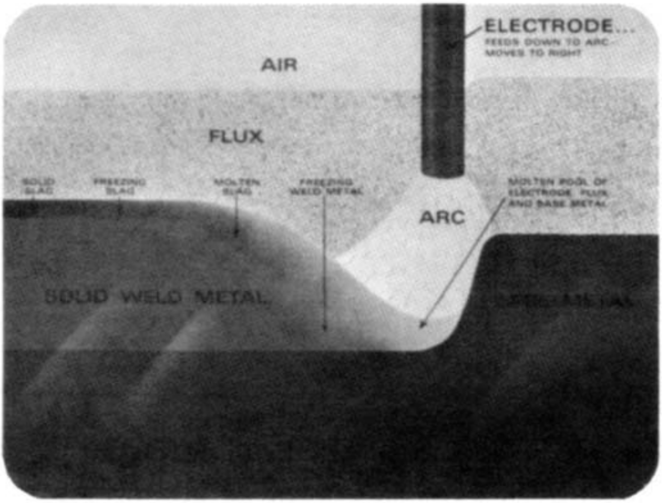

FIGURE 26.8 The mechanics of the submerged-arc process. The arc and the molten weld metal are buried in the layer of flux, which protects the weld metal from contamination and concentrates the heat into the joint. The molten flux arises through the pool, deoxidizing and cleansing the molten metal, and forms a protective slag over the newly deposited weld. *(The Lincoln Electric Company.)*

There are two general types of submerged-arc fluxes: bonded and fused. In *bonded* fluxes, the finely ground chemicals are mixed, treated with a bonding agent, and manufactured into a granular aggregate. The deoxidizers are incorporated in the flux. *Fused* fluxes are a form of glass resulting from fusing the various chemicals and then grinding the glass to a granular form. Fluxes are available that add alloying elements to the weld metal, enabling alloy weld metal to be made with mild-steel electrodes.

High currents can be used in submerged-arc welding, and extremely high heat can be developed. Because the current is applied to the electrode a short distance above its tip, relatively high amperages can be used on small-diameter electrodes. This results in extremely high current densities on relatively small cross sections of electrode. Currents as high as 600 A can be carried on electrodes as small as $\frac{5}{64}$ in, giving a density of the order of 100 000 A/in^2—6 to 10 times that carried on stick electrodes.

Because of the high current density, the melt-off rate is much higher for a given electrode diameter than with stick-electrode welding. The melt-off rate is affected by the electrode material, the flux, the type of current, the polarity, and the length of wire beyond the point of electric contact in the gun or head.

The insulating blanket of flux above the arc prevents rapid escape of heat and concentrates it in the welding zone. Not only are the electrode and base metal melted rapidly, but the fusion is deep into the base metal. The deep penetration allows the use of small welding grooves, thus minimizing the amount of filler metal per foot of joint and permitting fast welding speeds. Fast welding, in turn, minimizes the total heat input into the assembly and thus tends to prevent problems of heat distortion. Even relatively thick joints can be welded in one pass by the submerged-arc process.

Welds made under the protective layer of flux have good ductility and impact resistance and uniformity in bead appearance. Mechanical properties at least equal to those of the base metal are consistently obtained. In single-pass welds, the amount of fused base material is large compared to the amount of filler metal used. Thus in such welds the base metal may greatly influence the chemical and mechanical properties of the weld. For this reason, it is sometimes unnecessary to use electrodes of the same composition as the base metal for welding many of the low-alloy steels.

With proper selection of equipment, submerged-arc welding is widely applicable to the welding requirements of industry. It can be used with all types of joints and permits welding a full range of carbon and low-alloy steels, from 16-gauge (1.5-mm) sheet to the thickest plate. It is also applicable to some high-alloy, heat-treated, and stainless steels and is a favored process for rebuilding and hard surfacing. Any degree of mechanization can be used—from the hand-held semiautomatic gun to boom- or track-carried and fixture-held multiple welding heads.

The high quality of submerged-arc welds, the high deposition rates, the deep penetration, the adaptability of the process to full mechanization, and the comfort characteristics (no glare, sparks, spatter, smoke, or excessive heat radiation) make it a preferred process in steel fabrication. It is used extensively in ship and barge building, in railroad car building, in pipe manufacture, and in fabricating structural beams, girders, and columns where long welds are required. Automatic submerged-arc installations are also key features of the welding areas of plants turning out mass-produced assemblies joined with repetitive short welds.

The high deposition rates attained with submerged-arc welding are chiefly responsible for the economies achieved with the process. The cost reductions from changing from the manual shielded metal-arc process to the submerged-arc process are frequently dramatic. Thus a hand-held submerged-arc gun with mechanized travel may reduce welding costs more than 50 percent; with fully automatic multiarc equipment, it is not unusual for the costs to be but 10 percent of those attained with stick-electrode welding.

26.6.7 Other "Arc-Welding" Processes

Various adaptations of the arc-welding processes described have been made to meet specialized joining needs. In addition, there are processes using electrical energy to join metals that do not fall under the category of arc welding—including electrical resistance welding and ultrasonic, electron beam, and electrodeposition welding.

Electroslag welding is an adaptation of the submerged-arc process for joining thick materials in a vertical position. Figure 26.9 is a diagrammatic sketch of the electroslag process. It will be noted that whereas some of the principles of submerged-arc welding apply, in other respects the process resembles a casting operation.

In Fig. 26.9, a square butt joint in heavy plate is illustrated, but the electroslag process—with modifications in equipment and technique—is also applicable to T joints, corner joints, girth seams in heavy-wall cylinders, and other joints. The process is suited best for materials at least 1 in in thickness and can be used with multiple electrodes on materials up to 10 in thick without excessive difficulties.

As illustrated by the open square butt joint, the assembly is positioned for the vertical deposition of weld metal. A starting pad at the bottom of the joint prevents

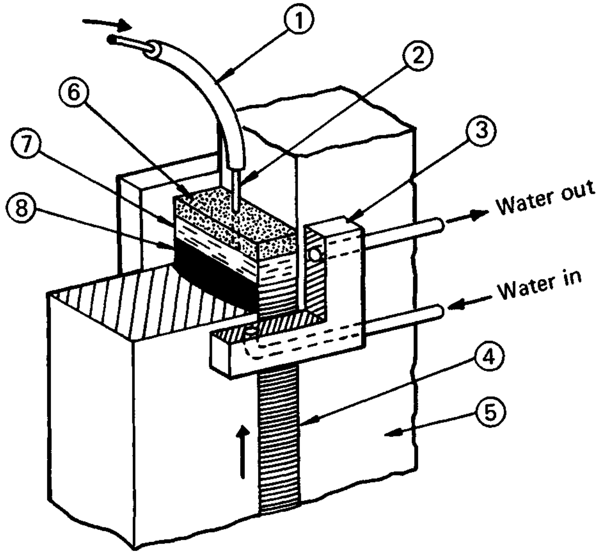

FIGURE 26.9 Schematic sketch of electroslag welding: (1) electrode guide tube, (2) electrode, (3) water-cooled copper shoes, (4) finished weld, (5) base metal, (6) molten slag, (7) molten weld metal, and (8) solidified weld metal. *(The Lincoln Electric Company.)*

the fall-out of the initially deposited weld metal and, since it is penetrated, ensures a full weld at this point. Welding is started at the bottom and progresses upward. Water-cooled dams, which may be looked on as molds, are placed on each side of the joint. These dams are moved upward as the weld-metal deposition progresses. The joint is filled in one *pass*—a single upward progression—of one or more consumable electrodes. The electrode or electrodes may be oscillated across the joint if the width of the joint makes this desirable.

At the start of the operation, a layer of flux is placed in the bottom of the joint and an arc is struck between the electrode (or electrodes) and the work. The arc melts the slag, forming a molten layer, which subsequently acts as an electrolytic heating medium. The arc is then quenched or shorted-out by this molten conductive layer. Heat for melting the electrode and the base metal subsequently results from the electrical resistance heating of the electrode section extending from the contact tube and from the resistance heating within the molten slag layer. As the electrode (or electrodes) is consumed, the welding head (or heads) and the cooling dams move upward.

In conventional practice, the weld deposit usually contains about one-third melted base metal and two-thirds electrode metal—which means that the base metal substantially contributes to the chemical composition of the weld metal. Flux consumption is low, since the molten flux and the unmelted flux above it "ride" above the progressing weld.

The flux used has a degree of electrical conductivity and low viscosity in the molten condition and a high vaporization temperature. The consumable electrodes may be either solid wire or tubular wire filled with metal powders. Alloying elements may be incorporated into the weld by each of these electrodes.

Weld quality with the electroslag process is generally excellent, because of the protective action of the heavy slag layer. Sometimes, however, the copper dams are provided with orifices just above the slag layer through which a protective gas—argon or carbon dioxide—is introduced to flush out the air above the weld and thus give additional assurance against oxidation. Such provisions are sometimes considered worthwhile when welding highly alloyed steels or steels that contain easily oxidized elements.

Electrogas welding is very similar to electroslag welding in that the equipment is similar and the joint is in the vertical position. As the name implies, the shielding is by carbon dioxide or an inert gas. A thin layer of slag, supplied by the flux-cored electrode, covers the molten metal, and the heat is supplied by an arc rather than by resistance heating, as in the electroslag process.

A disadvantage of the process is that it requires an external source of shielding gas. However, one advantage is that if the welding is stopped, the electrogas process can be started again with less difficulty than the electroslag process.

Stud arc welding is a variation of the shielded metal-arc process that is widely used for attaching studs, screws, pins, and similar fasteners to a large workpiece. The *stud* (or small part) itself—often plus a ceramic ferrule at its tip—is the arc-welding electrode during the brief period of time required for studding.

In operation, the stud is held in a portable pistol-shaped tool called a *stud gun* and positioned by the operator over the spot where it is to be weld-attached. At a press of the trigger, current flows through the stud, which is lifted slightly, creating an arc. After a very short arcing period, the stud is then plunged down into the molten pool created on the base plate, the gun is withdrawn from it, and the ceramic ferrule—if one has been used—is removed. The timing is controlled automatically, and the stud is welded onto the workpiece in less than a second. The fundamentals of the process are illustrated in Fig. 26.10.

Studs are of many shapes. All may be weld-attached with portable equipment. The stud may be used with a ceramic arc-shielding ferrule, as shown in Fig. 26.10, which prevents air infiltration and also acts as a dam to retain the molten metal, or it may have a granular flux, flux coating, or solid flux affixed to the welding end, as illustrated in Fig. 26.11. The flux may include any of the agents found in a regular electrode covering; most important to stud welding is a deoxidizer to guard against porosity.

Plasma-arc (or plasma-torch) welding is one of the newer welding processes which is used industrially, frequently as a substitute for the gas tungsten-arc process. In some applications, it offers greater welding speeds, better weld quality, and less sensitivity to process variables than the conventional processes it replaces. With the plasma torch, temperatures as high as 60 000°F are developed, and theoretically, temperatures as high as 200 000°F are possible.

The heat in plasma-arc welding originates in an arc, but this arc is not diffused as is an ordinary welding arc. Instead, it is constricted by being forced through a relatively small orifice. The *orifice,* or plasma gas, may be supplemented by an auxiliary source of shielding gas.

Orifice gas refers to the gas that is directed into the torch to surround the electrode. It becomes ionized in the arc to form the plasma and emerges from the orifice in the torch nozzle as a plasma jet. If a shielding gas is used, it is directed onto the workpiece from an outer shielding ring.

The workpiece may or may not be part of the electric circuit. In the *transferred-arc system,* the workpiece is a part of the circuit, as in other arc-welding processes. The arc *transfers* from the electrode through the orifice to the work. In the *non-transferred system,* the constricting nozzle surrounding the electrode acts as an elec-

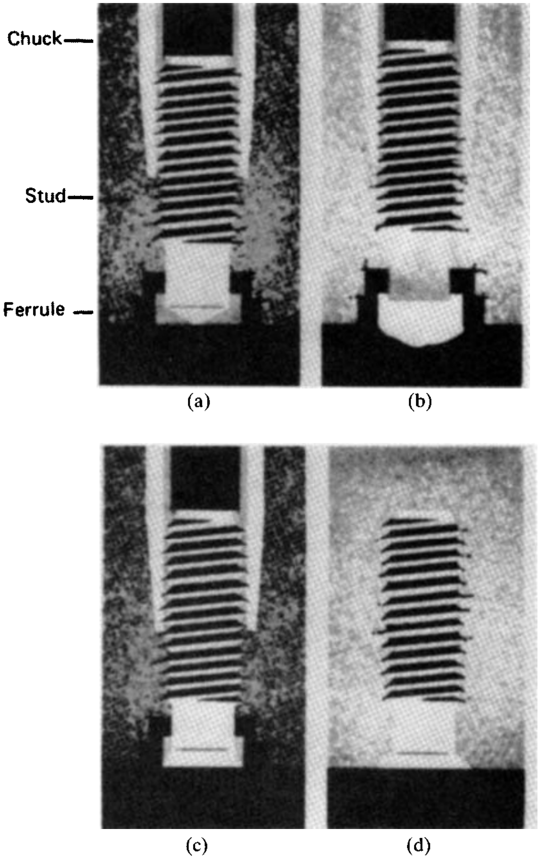

FIGURE 26.10 Principles of stud welding, using a ceramic ferrule to shield the pool. (*a*) The stud with ceramic ferrule is grasped by the chuck of the gun and positioned for welding. (*b*) The trigger is pressed, the stud is lifted, and the arc is created. (*c*) With the brief arcing period completed, the stud is plunged into the molten pool on the base plate. (*d*) The gun is withdrawn from the welded stud and the ferrule is removed. *(The Lincoln Electric Company.)*

tric terminal, and the arc is struck between it and the electrode tip; the plasma gas then carries the heat to the workpiece. Figure 26.12 illustrates transferred and nontransferred arcs.

The advantages gained by using a constricted-arc process rather than the gas tungsten-arc process include greater energy concentration, improved arc stability, higher welding speeds, and lower width-to-depth ratio for a given penetration. *Keyhole welding*—or penetrating completely through the workpiece—is possible.

The *atomic-hydrogen process of arc welding* may be regarded as a forerunner of gas-shielded and plasma-torch arc welding. Although largely displaced by other pro-

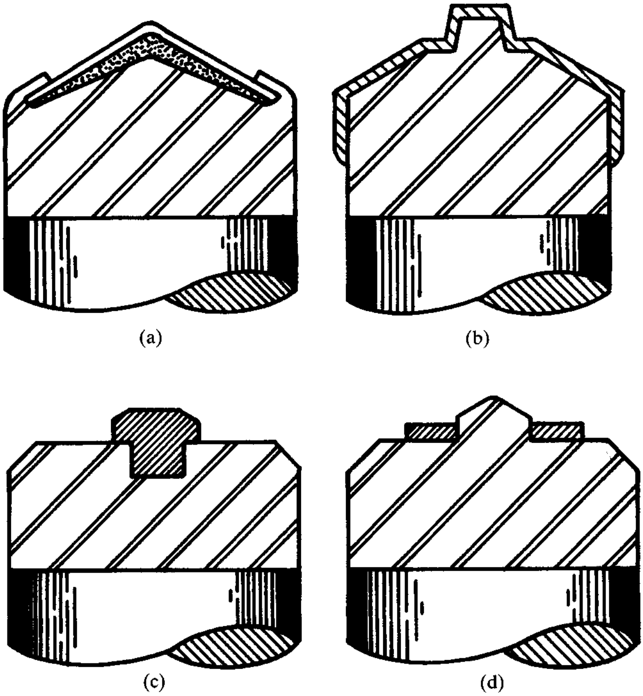

FIGURE 26.11 Three methods of containing flux on the end of a welding stud: (*a*) granular flux; (*b*) flux coating; (*c*) and (*d*) solid flux. *(The Lincoln Electric Company.)*

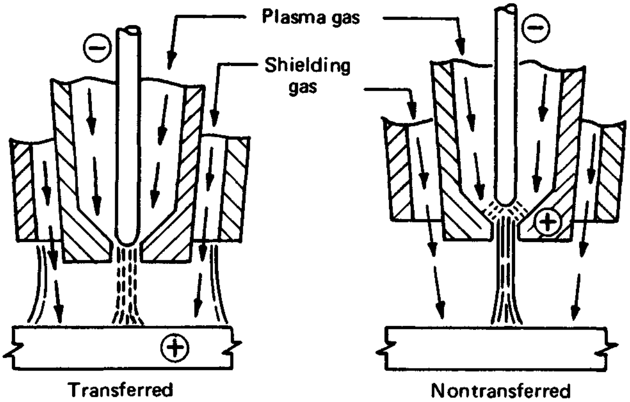

FIGURE 26.12 Transferred and nontransferred arcs. *(The Lincoln Electric Company.)*

cesses that require less skill and are less costly, it is still preferred in some manual operations where close control of heat input is required.

In the atomic-hydrogen process, an arc is established between two tungsten electrodes in a stream of hydrogen gas using alternating current. As the gas passes through the arc, molecular hydrogen is dissociated into atomic hydrogen under the intense heat. When the stream of hydrogen atoms strikes the workpiece, the environmental temperature is then at a level where recombining into molecules is possible. As a result of the recombining, the heat of dissociation absorbed in the arc is liberated, supplying the heat needed for fusing the base metal and any filler metal that may be introduced.

The atomic-hydrogen process depends on an arc, but is really a heating torch. The arc supplies the heat through the intermediate of the molecular-dissociation, atom-recombination mechanism. The hydrogen gas, however, does more than provide the mechanism for heat transfer. Before entering the arc, it acts as a shield and a coolant to keep the tungsten electrodes from overheating. At the weld puddle, the gas acts as a shield. Since hydrogen is a powerful reducing agent, any rust in the weld area is reduced to iron, and no oxide can form or exist in the hydrogen atmosphere. Weld metal, however, can absorb hydrogen, with unfavorable metallurgical effects. For this reason, the process gives difficulties with steels containing sulfur or selenium, since hydrogen reacts with these elements to form hydrogen sulfide or hydrogen selenide gases. These are almost insoluble in molten metal and either bubble out of the weld pool vigorously or become entrapped in the solidifying metal, resulting in porosity.

26.7 ARC-WELDING CONSUMABLES

Arc-welding consumables are the materials used up during welding, such as electrodes, filler rods, fluxes, and externally applied shielding gases. With the exception of the gases, all the commonly used consumables are covered by AWS specifications.

Twenty specifications in the AWS A5.x series prescribed the requirements for welding electrodes, rods, and fluxes.

26.7.1 Electrodes, Rods, and Fluxes

The first specification for mild-steel-covered electrodes, A5.1, was written in 1940. As the welding industry expanded and the number of types of electrodes for welding steel increased, it became necessary to devise a system of electrode classification to avoid confusion. The system used applies to both the mild-steel A5.1 and the low-alloy steel A5.5 specifications.

Classifications of *mild and low-alloy steel electrodes* are based on an *E* prefix and a four- or five-digit number. The first two digits (or three, in a five-digit number) indicate the minimum required tensile strength in thousands of pounds per square inch. For example, 60 = 60 kpsi, 70 = 70 kpsi, and 100 = 100 kpsi. The next to the last digit indicates the welding position in which the electrode is capable of making satisfactory welds: 1 = all positions—flat, horizontal, vertical, and overhead; 2 = flat and horizontal fillet welding (see Table 26.1). The last digit indicates the type of current to be used and the type of covering on the electrode (see Table 26.2).

Originally a color identification system was developed by the National Electrical Manufacturers Association (NEMA) in conjunction with the AWS to identify the electrode's classification. This was a system of color markings applied in a specific relationship on the electrode, as in Fig. 26.13*a*. The colors and their significance are

TABLE 26.1 AWS A5.1-69 and A5.5-69 Designations for Manual Electrodes

a. The prefix *E* designates arc-welding electrode.

b. The first two digits of four-digit numbers and the first three digits of five-digit numbers indicate minimum tensile strength:

E 60XX	60 000 psi minimum tensile strength
E 70XX	70 000 psi minimum tensile strength
E110XX	110 000 psi minimum tensile strength

c. The next-to-last digit indicates position:

EXX1X	All positions
EXX2X	Flat position and horizontal fillets

d. The suffix (for example, EXXXX-*A1*) indicates the approximate alloy in the weld deposit:

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

listed in Tables 26.3 and 26.4. The NEMA specification also included the choice of imprinting the classification number on the electrode, as in Fig. 26.13*b*.

Starting in 1964, new and revised AWS specifications for covered electrodes required that the classification number be imprinted on the covering, as in Fig. 26.13*b*. However, some electrodes can be manufactured faster than the imprinting equipment can mark them, and some sizes are too small to be legibly marked with an imprint. Although AWS specifies an imprint, the color code is accepted on electrodes if imprinting is not practical.

Bare mild-steel electrodes (electrode wires) for submerged-arc welding are classified on the basis of chemical composition, as shown in Table 26.5. In this classifying system, the letter *E* indicates an electrode as in the other classifying systems, but

TABLE 26.2 AWS A5.1-69 Electrode Designations for Covered Arc-Welding Electrodes

Designation	Current	Covering type
EXX10	dc+ only	Organic
EXX11	ac or dc+	Organic
EXX12	ac or dc−	Rutile
EXX13	ac or dc±	Rutile
EXX14	ac or dc±	Rutile, iron-powder (approx. 30%)
EXX15	dc+ only	Low-hydrogen
EXX16	ac or dc+	Low-hydrogen
EXX18	ac or dc+	Low-hydrogen, iron-powder (approx. 25%)
EXX20	ac or dc±	High iron-oxide
EXX24	ac or dc±	Rutile, iron-powder (approx. 50%)
EXX27	ac or dc±	Mineral, iron-powder (approx. 50%)
EXX28	ac or dc+	Low-hydrogen, iron-powder (approx. 50%)

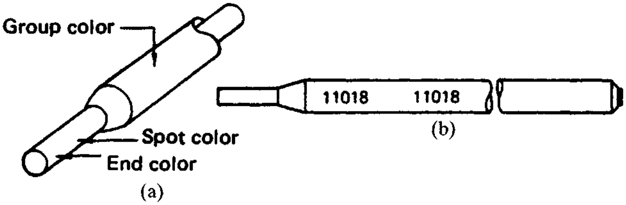

FIGURE 26.13 (*a*) National Electrical Manufacturers Association color-code method to identify an electrode's classification. (*b*) American Welding Society imprint method. *(The Lincoln Electric Company.)*

here the similarity stops. The next letter, *L, M,* or *H,* indicates low, medium, or high manganese, respectively. The following number or numbers indicate the approximate carbon content in hundredths of a percent. If there is a suffix *K,* this indicates a silicon-killed steel.

Fluxes for submerged-arc welding are classified on the basis of the mechanical properties of the weld deposit made with a particular electrode. The classification designation given to a flux consists of a prefix *F* (indicating a flux) followed by a two-digit number representative of the tensile-strength and impact requirements for test welds made in accordance with the specification. This is then followed by a

TABLE 26.3 Color Identification for Covered Mild-Steel and Low-Alloy Steel Electrodes

Spot color	End color			
	No color	Blue	Black	Orange
	Group color—No color			
	XX10, XX11, XX14, XX24, XX27, XX28, and all 60 XX			
No color	E6010	E7010G	....	EST
White	E6012	E7010-Ai	....	EC1
Brown	E6013	....	E7014	
Green	E6020			
Blue	E6011	E7011G		
Yellow	....	E7011-A1	E7024	
Black	....	....	E7028	
Silver	E6027			
	Group color—Silver			
	All XX13 and XX20 except E6013 and E6020			
Brown				
White				
Green	....	E7020G		
Yellow	....	E7020-A1		

TABLE 26.4 Color Identification for Covered Low-Hydrogen Low-Alloy Electrodes

Spot color	End color									
	No color	Blue	Black	White	Gray	Brown	Violet	Green	Red	Orange
	Group color—Green									
	XX15, XX16, and XX18, except E6015 and E6016									
Red	E7015G	E7015	....	....	E8015G	E9015G	....	E10015G	....	E12015G
White	....	E7015-A1	E90150-B3L	....	....	E9015-D1				
Brown										
Green	....	....	E8015-B2L	....	....	E9015-B3				
Bronze	....	....	E8015-B4L	....	....	E8015-B4				
Orange	E7016G	E7016	E7018	E8016-C3	....	E9016G	....	E10016G	....	E12016G
Yellow	....	E7016-A1	E7018-A1	E8016G	....	E9016-D1	....	E10015-D2	E11016G	
Black	....	....	E8018-C3	E8016-B1	E8018-B1	....	E9018-B3			
Blue	E7018G	....	E8018G	E8016-C1	E8018-C1	E9016-B3	E9018G	E10018G	E11018G	E12018G
Violet	....	....	....	E8016-C2	E8018-C2	E8016-B4	E9018-D1	E10018-D2		
Gray	....	....	E8018-B4	E8016-B2	E8018-B2	....		E10016-D2		
Silver	....	....	Mil-12018							

TABLE 26.5 AWS A5.17-69 Chemical-Composition Requirements for Submerged-Arc Electrodes

AWS classification	Chemical composition, percent						
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Copper†	Total other elements
Low manganese classes:							
EL8	0.10	0.30–0.55	0.05	0.035	0.03	0.15	0.50
EL8K	0.10	0.30–0.55	0.10–0.20	0.035	0.03	0.15	0.50
EL12	0.07–0.15	0.35–0.60	0.05	0.035	0.03	0.15	0.50
Medium manganese classes:							
EM5K‡	0.06	0.90–1.40	0.40–0.70	0.035	0.03	0.15	0.50
EM12	0.07–0.15	0.85–1.25	0.05	0.035	0.03	0.15	0.50
EM12K	0.07–0.15	0.85–1.25	0.15–0.35	0.035	0.03	0.15	0.50
EM13K	0.07–0.19	0.90–1.40	0.45–0.70	0.035	0.03	0.15	0.50
EM15K	0.12–0.20	0.85–1.25	0.15–0.35	0.035	0.03	0.15	0.50
High manganese class:							
EH14	0.10–0.18	1.75–2.25	0.05	0.035	0.03	0.15	0.50

†The copper limit is independent of any copper or other suitable coating which may be applied to the electrode.

‡This electrode contains 0.05 to 0.15 percent titanium, 0.02 to 0.12 percent zirconium, and 0.05 to 0.15 percent aluminum, which is exclusive of the "Total other elements" requirement.

Note: Analysis shall be made for the elements for which specific values are shown in this table. If, however, the presence of other elements is indicated in the course of routine analysis, further analysis shall be made to determine that the total of these other elements is not present in excess of the limits specified for "Total other elements" in the last column of the table. Single values shown are maximum percentages.

set of letters and numbers corresponding to the classification of the electrode used with the flux.

Gas-shielded flux-cored electrodes are available for welding the low-alloy high-tensile steels. *Self-shielded flux-cored electrodes* are available for all-position welding, as in building construction. Fabricators using or anticipating using the flux-cored arc-welding processes should keep in touch with the electrode manufacturers for new or improved electrodes not included in present specifications.

Mild-steel electrodes for gas metal-arc welding of mild and low-alloy steels are classified on the basis of their chemical compositions and the as-welded mechanical properties of the weld metal. Tables 26.6 and 26.7 are illustrative.

AWS specifications for electrodes also cover those used for welding the stainless steels, aluminum and aluminum alloys, and copper and copper alloys, as well as for weld surfacing.

Shielding gases are consumables used with the MIG and TIG welding processes. The AWS does not write specifications for gases. There are federal specifications, but the welding industry usually relies on *welding grade* to describe the required purity.

The primary purpose of a shielding gas is to protect the molten weld metal from contamination by the oxygen and nitrogen in air. The factors, in addition to cost, that affect the suitability of a gas include the influence of the gas on the arcing and metal-transfer characteristics during welding, weld penetration, width of fusion and surface shape, welding speed, and the tendency to undercut. Among the inert gases—helium, argon, neon, krypton, and xenon—the only ones plentiful enough for practical use in welding are helium and argon. These gases provide satisfactory shielding for the more reactive metals, such as aluminum, magnesium, beryllium, columbium, tantalum, titanium, and zirconium.

Although *pure* inert gases protect metal at any temperature from reaction with constituents of the air, they are not suitable for all welding applications. Controlled quantities of reactive gases mixed with inert gases improve the arc action and metal-transfer characteristics when welding steels, but such mixtures are not used for reactive metals.

Oxygen, nitrogen, and carbon dioxide are reactive gases. With the exception of carbon dioxide, these gases are not generally used alone for arc shielding. Carbon dioxide can be used alone or mixed with an inert gas for welding many carbon and low-alloy steels. Oxygen is used in small quantities with one of the inert gases—usually argon. Nitrogen is occasionally used alone, but it is usually mixed with argon as a shielding gas to weld copper. The most extensive use of nitrogen is in Europe, where helium is relatively unavailable.

26.8 DESIGN OF WELDED JOINTS

While designers need some basic knowledge of welding processes, equipment, materials, and techniques, their main interest is in how to transfer forces through welded joints most effectively and efficiently. Proper joint design is the key to good weld design.

The loads in a welded-steel design are transferred from one member to another through welds placed in weld joints. Both the type of joint and the type of weld are specified by the designer.

Figure 26.14 shows the joint and weld types. Specifying a joint does not by itself describe the type of weld to be used. Thus 10 types of welds are shown for making a