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TECHNOLOGICAL ADVANCES IN JOINING

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Technological Advances in Joining

by

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METALS AND CERAMICS INFORMATION CENTER
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INTRODUCTION

In common with other areas of materials processing, significant growth in the technology of joining has occurred in recent years. However, growth during the middle and late 1970s has been largely characterized by the continued development, improvement, and application of established processes, rather than by the introduction of new processes. Thus, while plasma-arc welding was pioneered in the 1950s, recent efforts have been directed toward broadening the capabilities of this process and using it in applications where high deposition rates and minimum base metal dilution are required. Similar trends have been also observed in electron-beam welding, laser welding, and other methods of joining. Technical advances are most evident in the field of mechanized welding where substantial progress has been made to extend the usefulness of programmable industrial robots by the inclusion of a welding capability.

During the 1960s, progress in materials joining technology was spurred by the demanding requirements of the aircraft and aerospace industries. Existing processes were improved and mechanized and new ones were developed to meet specific needs. New methods were developed to assess joint quality, and extensive research was conducted to expand the understanding of basic joining phenomena. Many of the advances resulting from these concentrated efforts are presently being utilized by various segments of our industrial economy. The aircraft and aerospace industries continue to advance the cause of joining; however, as indicated, much of the recent growth in this area appears to be attributable to factors other than continued process development:

- The need for increases in productivity to compete effectively in national and international markets has produced substantial advances in the mechanization of many welding processes. The use of industrial robots with resistance-spot welding capabilities is widespread in the automotive industry, and similar robots are being equipped to perform many arc welding functions in areas where high production rates must be maintained. While increased productivity is characteristic of such robots, their use by industry is predicated on their ability to produce high-quality welded joints with consistent properties. Also, the availability of robots provides an opportunity for industry to free welders from the boredom and hazards associated with many welding applications.

- Demands for increased productivity and joint consistency have resulted in the development of highly mechanized systems for welding nonrotatable joints in pipe and tubing. Among the most notable achievements in this area are systems designed for the gas metal-arc or flux-cored arc welding of girth joints in large-diameter, high-strength steel line pipe. While this equipment is unlikely to displace the manual welder entirely, it has been used to construct several thousand miles of land and marine pipeline for the transmission of natural gas and crude oil. Other welding processes have been considered for this application with varying degrees of success. Several high-quality mechanized gas tungsten-arc welding systems have been developed for making circumferential joints in tubing with diameters ranging from a fraction of an inch to several inches. Some of these systems are relatively simple, but others are very sophisticated and include programmable control of welding parameters such as current, voltage, welding speed, wire feed rate, and the movements of the welding head. One of the many uses for this equipment is the welding of power plant piping.

- The availability of high technology has contributed toward growth in the materials joining area, as evidenced by the increasing use of solid-state devices in welding power supplies, wire feed controls, and other control devices. Such units are smaller and lighter than those that were previously available; also, they are more reliable, require less maintenance, and provide better control of the process variables. Similarly, the availability of microprocessors has expanded the capabilities of industrial robots.

- Advances in joining technology have been spurred by other considerations. The requirements of the Occupational Safety and Health Act has prompted extensive studies of the potential hazards associated with welding and related operations, and as a result, a large background of useful data has been accumulated. The producers of welding consumables have made substantial progress in reducing the levels of atmospheric contaminants by modifying the composition of electrode coverings and fluxes, and equipment and procedures have been developed to minimize these and other hazards. Also, there is renewed interest in submerged-arc welding, a process that is relatively hazard-free in addition to its other technical attributes.

Technological growth has been also stimulated by factors other than those discussed above such as technical requirements, economic factors, materials compatibility, and materials conservation.

The Metals and Ceramics Information Center has taken note of developments in materials joining on many occasions. A 1973 report, "Advances in Joining Technology—The '60s and Beyond", reviewed many of the accomplishments that were made during the period when progress resulted from the needs of the aircraft and aerospace industries as well as those of industries concerned with the production of consumer goods. Joining process developments were emphasized in this publication. Progress in the mechanization of welding operations was discussed in a 1974 report, "Automation in Welding". Because advances have continued at a pace in recent years, it appears wise to review this area of technology at the start of a new decade.

Many of the significant advances that have contributed to growth in materials joining during the middle and late 1970s are described in this report. For convenience, the subject matter is organized in two sections to acknowledge the accomplishments in the process development and process automation areas. Processes and applications in joining are generally emphasized, rather than the results of research directed toward the discovery of solutions to metallurgical problems encountered in joining specific base metals; e.g., causes of porosity in titanium welds, effect of microstructure on weld metal fracture toughness, causes of cracking in austenitic stainless steel welds, etc. Such subjects are too numerous and too complex to be covered adequately in this document.

Developments are discussed with respect to specific joining processes, the characteristics of which are reviewed briefly to establish a common basis for proceeding with the details of the advancements. Understandably, only a portion of the efforts leading to these advances can be included in this report; however, references are cited for those who wish to pursue the respective subjects further.

PROCESS DEVELOPMENTS

Fusion Welding Processes

Shielded Metal-Arc Welding

Shielded metal-arc welding, a process in which fusion is produced by an arc established between a covered electrode and the workpieces, is the most common, widely used arc welding process. Shielding of the arc and molten weld metal is provided by the gases that are produced when the electrode covering decomposes. Filler metal is provided by the metallic portion of the electrode. This process is applicable to a wide range of ferrous and nonferrous metals and alloys. Shielded metal-arc welding is the mainstay of the metal fabricating industry; however, its importance has gradually dwindled with the increased use of processes that can be mechanized to improve productivity and weldment consistency (e.g., gas metal-arc welding, flux-cored arc welding, etc.).

Welding of Microalloyed Pipe Steels. In response to the need to transport gas and liquid hydrocarbons from their source to the marketplace, extensive research has been conducted to develop improved filler metals and welding procedures for joining large-diameter line pipe made from the high-strength low-alloy steels that were developed during the last decade for Arctic service. These acicular-ferrite and pearlite-reduced steels contain molybdenum and very small alloying additions of niobium and/or vanadium; pipe produced from these steels meets the requirements of API Grades X60, X65, and X70. The low carbon content of these steels and their fine grained microstructure combine to provide the strength and fracture toughness required for pipeline applications in cold regions; the low carbon content also enhances the weldability of these steels.

Shielded metal-arc welding of girth joints in line pipe made from microalloyed steels is usually accomplished with cellulosic-covered electrodes whose strength is similar to that of the base metal; modified versions of these mild- and low-alloy steel electrodes have been developed to improve the weldability of these steels and increase the fracture toughness of the welded joints at low temperatures. Among the studies that have made significant contributions to the background of data on the weldability of these pipe steels are those conducted by Sawhill[1], Grosse-Woerdmann[2], Bryhan and Troyer[3], and Liegeois and his associates.[4] The results of these research efforts indicate that the microalloyed pipe steels can be successfully welded under field conditions if the arc length and heat input are properly monitored. Control of the heat input and cooling rate is necessary to achieve the required fracture toughness and avoid the formation of microstructures that are characterized by very high hardnesses in the heat-affected zones, especially in the root pass. Welds with such microstructures are subject to underbead cracking induced by the presence of hydrogen and residual stresses. Post-weld tempering may be needed to reduce such high hardnesses.

To cite some factual data, Liegeois, et al, examined the effects of preheat and welding heat input on joint properties during the fabrication of girth welds between sections of 48-inch-diameter X70 pipe made from a Mn-Mo-Nb steel. Welding was done with various commercially available cellulosic-covered electrodes in a cold chamber where the ambient temperature was maintained at -22 F (-30 C); joints were made without preheating and with preheating of the joint area to 212 F (100 C). The following results were observed:

- The hardness in the heat-affected zones and along the axis of the weld bead was more a function of the heat input during welding than the presence or absence of preheating.
- Charpy V-notch impact values were above 22 ft-lb at -13 F (-25 C) along the fusion line of the weld and over 66 ft-lb at a distance of 0.080 inch from the fusion line. Again, the presence or absence of preheating had little effect on notch toughness in the heat-affected zone. Impact values at -40 F (-40 C) were slightly lower than those observed at -13 F (-25 C). Impact values measured along the axis of the weld were about 20 ft-lb at temperatures down to -4 F (-20 C).
- Little significant difference in the weld deposit chemistry was observed between welds made with or without preheating. Heat-affected zone microstructures were independent of the preheating conditions and no underbead cracking was observed.

The cold chamber welding tests demonstrated that the low-carbon Mn-Mo-Nb pipe steels could be welded under adverse conditions with cellulosic-covered electrodes; the welded joints were not susceptible to cold cracking and adequate toughness appeared to be retained in the weld heat-affected zones.

Firecracker Welding. Because of its potential beneficial effects on productivity, firecracker welding, a variation of the shielded metal-arc welding process, has been investigated for shipyard welding applications. Although the basic process dates back to the 1930s, it has not been widely accepted in this country, probably because of the trend toward the use of semiautomatic and automatic welding processes. However, it has been used successfully over the years in various European countries and in Japan for repetitive and/or limited access welding applications. Firecracker welding is a method for automatically making joints with a relatively long electrode that has a thick, nonconductive covering. While it is best suited for fillet welding, other joint configurations can be welded in this manner if adequate penetration can be achieved.

Firecracker welding is done in the flat or nearly flat position. In making a fillet weld (Figure 1), the welding electrode is positioned in the joint and is held in place with tape or a copper retaining bar. The arc is initiated by shorting the electrode to the workpiece. As the arc progresses along the electrode, the electrode melts and metal is deposited in the joint; shielding is provided by the gases that are produced as the electrode covering decomposes. Following arc initiation, the process is completely automatic and proceeds until the electrode is consumed. Firecracker welding can be characterized as follows:

- The size of a firecracker weld is governed by the type and diameter of the welding electrode. The length of such a weld is dependent on electrode length only.

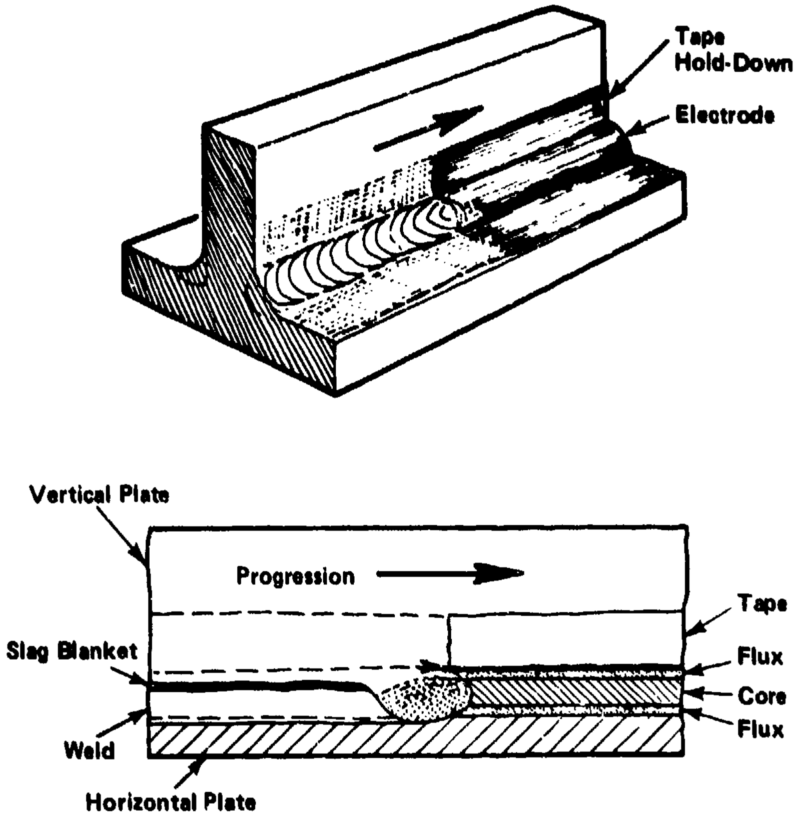


FIGURE 1. Sketch of Firecracker Fillet Welding Process[5]

- Welding current is the only independent electrical variable. Arc length is dependent on the thickness of the electrode covering.
- Welding speed is a direct function of arc current; that is, higher welding speeds can be achieved with higher currents. Maximum current levels are dependent on the type and diameter of the welding electrode and recommended limits should not be exceeded.
- Firecracker weld quality is generally equivalent to that of welds made by manual means with the same type of electrode.
- Limited skills are required for firecracker welding and one welder can handle several operations simultaneously.

The advantages of firecracker welding for applications in the shipbuilding industry have been demonstrated in work conducted for a major shipyard and the Maritime Administration.[5] During this program, research efforts were directed toward the development of fillet welding procedures, the selection of the operating parameters, and the specification of the required consumables. The results of screening tests conducted with cellulosic, rutile, low hydrogen, and iron powder covered electrodes indicated that the E6027 and E7024 electrodes were most suitable for firecracker welding based on bead shape, surface profile, reproducibility, ease of slag removal, and other considerations. Also, because of the thick covering which contained as much as 50 percent iron powder, these electrodes could be used to produce fillet welds with sizes greater than those obtainable with other covered electrodes. As indicated in Table 1, welding was best accomplished with an alternating current power source. Efforts were made to control the direction of the welding arc by shaping or slotting the electrode covering. These efforts to improve the consistency of welding met with little success other than a slight increase in arc stability that was observed with electrodes whose covering was slotted. The following methods to maintain the location of the electrode during welding were studied: copper retaining bars, magnetic hold-down devices, and glass fiber tape. While copper retaining bars were most suitable for this purpose, they were costly to fabricate and maintain. Glass fiber tape proved to be an effective electrode retention material for welds of limited length. In the course of this investigation, joints that simulated those encountered in ship construction (e.g., the attachment of stiffeners to decking) were successfully welded in lengths up to 60 inches with special electrodes. Short multipass welds were also made by firecracker welding. Preferred conditions for welding groove and fillet joints are shown in Table 1b.

TABLE 1a. Summary of Initial Welding Parameter Studies(5)

Electrode	Diameter, in. (mm)	Voltage, V	Current, A	Polarity
E6027	1/4 (6.35)	35–39	235–240	AC
E6027	7/32 (5.56)	37–39	225–235	AC
E6027	1/4 (6.35)	33–40	230–250	DCRP
E6027	1/4 (6.35)	30–35	195–210	DCSP
E7024	1/4 (6.35)	27–32	235–250	AC
E7024	7/32 (5.56)	27–32	210–220	AC
E7024	1/4 (6.35)	32–36	240–260	DCRP
E7024	1/4 (6.35)	34–36	235–250	DCSP

(a) All values shown for ac welding are maximums; dc welding resulted in arc blow, poor welds or much spatter.

TABLE 1b. Preferred Welding Parameters for Groove and Fillet Welds(5)

Electrode Type	Diameter, in. (mm)	Groove Welding: Voltage, V	Groove Welding: Current, A	Groove Welding: Average AxV/1000	Fillet Welding: Voltage, V	Fillet Welding: Current, A	Fillet Welding: Average AxV/1000
6027	7/32 (5.56)	35–40	235–245	9.0	36–38	195–200	7.3
6027	1/4 (6.35)	30–34	245–250	8.8	35–38	235–240	8.7
7024	7/32 (5.56)	30–34	245–255	8.0	33–36	205–210	7.2
7024	1/4 (6.35)	27–30	270–280	8.8	27–32	235–250	7.2

Firecracker welding with covered strip electrodes has been accomplished in the Soviet Union; the width of these electrodes varied from 0.2 to 0.6 inch. This process variation could be used to increase productivity during the strip surfacing of massive components such as reactor vessels.

Plasma-Arc V. .ding and Surfacing

Plasma-arc welding can be considered as a special version of gas tungsten-arc welding in which the heat required for fusion is provided by an arc established between the electrode and the workpiece. In the basic transferred plasma-arc process, a low-current pilot arc is initiated between the electrode and a constricting nozzle by a high-frequency generator. As the orifice gas passes through the nozzle, it is constricted, heated to very high temperatures by the pilot arc, and ionized. The ionized gas forms a low resistance path to initiate the welding arc between the electrode and the workpiece. The energy intensity and velocity of the plasma jet is dependent on the type of orifice gas, the gas pressure, the shape and diameter of the constricting nozzle, and the operating variables. Because of the effects of arc constriction on the thermal and electrical characteristics of the arc, plasma-arc welding provides the following advantages over those associated with gas tungsten-arc welding:

- Greater arc stability and less sensitivity to changes in the electrode-to-work distance
- Greater penetration, narrower welds
- Reduced sensitivity to dimensional mismatch of joint members
- Higher welding speeds.

Welding can be done in the melt-in or keyhole modes. In melt-in welding, the arc melts but does not penetrate the base metal. In keyhole welding, the arc penetrates through the base metal to form the keyhole. Surface tension forces close the keyhole behind the arc as it progresses along the joint. Filler metal can be added as needed.

While continuous current provided by a direct current power source is used most commonly for plasma-arc welding, welding can be also done with pulsed current. Pulsed direct-current operation provides many of the advantages associated with pulsed-current gas tungsten-arc or gas metal-arc welding. The results of one investigation produced convincing evidence that penetration was enhanced by the use of pulsed current.[6] In plasma-arc welding, pulsing the current at 5 to 20 pulses/sec had a more pronounced effect on the depth of penetration than it did in gas tungsten-arc welding. Also, the ability to vary the orifice gas flow rate provided an additional means to control the amount of penetration achieved at a given current level during plasma-arc welding. The pulsed-current mode of operation had an equally beneficial effect on the depth-to-width ratio of the welds. For example, during bead-on-plate welding, the amount of penetration achieved with pulsed plasma-arc and pulsed gas tungsten-arc welding was 0.068 and 0.042 inch, respectively, for the same current levels and the same pulsing parameters (peak/background current ratio was 140/20 amperes; pulsing rate was 5 pulses/sec). Under the same conditions, the depth-to-width ratios were 0.50 and 0.23, respectively. The results of a more detailed comparison of pulsed plasma-arc and pulsed gas tungsten-arc welding substantiated the conclusions of the earlier research studies and provided additional insight on the effects of low- and high-frequency pulsing rates, various pulse time ratios, various peak and background current levels, etc.[7]

While plasma arc welding can be used to weld all metals that are considered fusion weldable by other means, it has not received the attention that it deserves in this country. Its use has been largely confined to applications where joint quality, consistency, and reproducibility are specified to exacting standards. Since references to conventional plasma-arc welding applications abound in the technical literature, they will not be covered in this report. Instead, selected developments that have extended process capabilities and improved productivity will be discussed in the following sections.

Plasma-GMA Welding. * This process combines the features of plasma-arc and gas metal-arc welding. It was developed in the Netherlands in the early 1970s and has been used for both welding and cladding operations. Welding experts recognize that gas metal-arc welding is a compromise at best because arc current must (1) control the melting rate of the filler metal, (2) control drop detachment and transfer across the arc, (3) maintain the arc plasma, and (4) preheat and melt the base metal. In plasma-GMA welding, the gas metal arc and the plasma arc are separate and can be independently controlled. As a result, the current through the filler wire and the current transferred to the workpiece can be individually specified to produce the desired melt-off rate and melting of the base metal. In comparison with conventional gas metal-arc welding and plasma-arc welding, this combined process provides higher deposition rates, more penetration during welding, and less dilution during cladding.

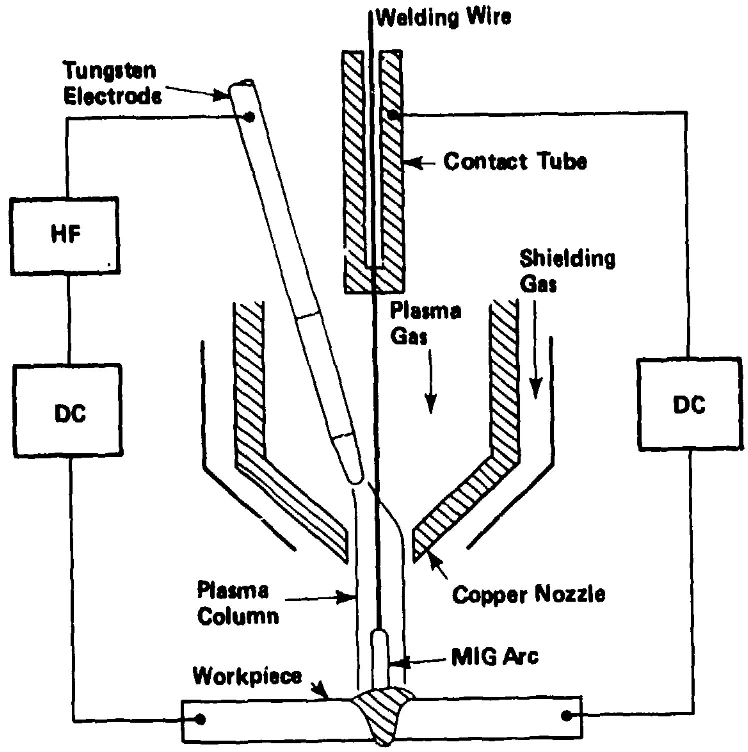
Torches used for plasma-GMA welding and surfacing are shown in Figures 2a and 2b along with power supply requirements. These torches differ in the manner in which the plasma arc is established. The plasma arc established between the electrode and workpiece in the torch shown in Figure 2a is initiated by a pilot arc produced by a high-frequency generator. In the torch shown in Figure 2b, the plasma arc established between the nozzle and the workpiece is initiated by the gas metal arc. Regardless of torch configuration, the current through the filler metal affects the thermal and electrical characteristics of the arc in a manner that bears on the applicability of this process. Below a certain transition current, a high-intensity columnar arc that is admirably suited for welding is produced; filler metal is transferred across this arc in the form of small drops. Above the transition current, a lower intensity rotating arc is formed and filler metal is transferred across the arc in a fine spray of extremely small droplets. The penetration achieved with this type of arc is very shallow and the deposition rate is very high (20 lb/hr or more); weld deposits can be made with minimum effects on base metal properties and minimum dilution. The rotating arc is used for cladding and surfacing applications.

As noted previously, the plasma arc can be used for welding any base metal. Selected plasma-GMA welding applications have been reviewed:

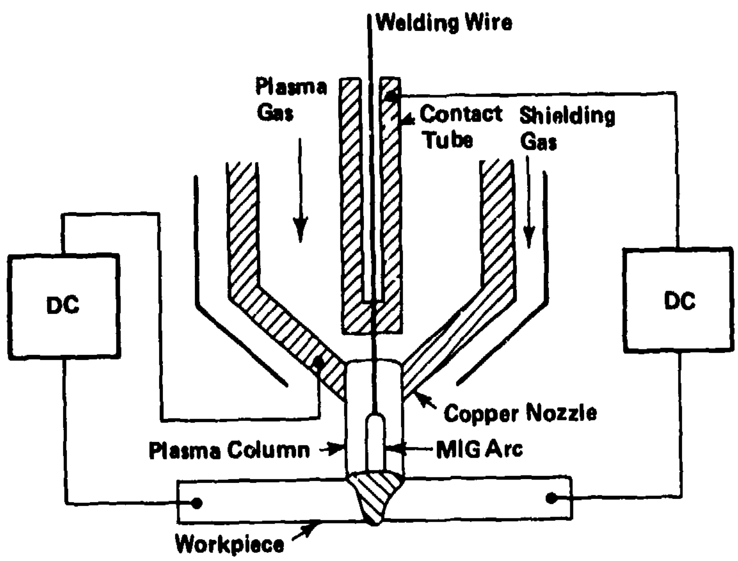
- To overcome the porosity in aluminum welds that is produced by gas metal-arc, plasma-arc, and gas tungsten-arc welding, the plasma-GMA process was used to weld the longitudinal seams in 6.6-inch-diameter 5000-series aluminum tubing with a wall thickness of 0.6 (or 0.8) inch.[8] Longitudinal joints with minimum porosity levels were produced in two passes, one from each side of the joint, at 12 to 16 ipm with mechanized equipment designed to handle tubing with a length of 6 feet. In another application, a fillet weld was used to attach an aluminum flange to an aluminum tube with a diameter of 8.4 inches. Including handling time, the single-pass flange-to-tubing joint was made in 5 minutes by plasma-GMA welding, a 700 percent increase in productivity over gas metal-arc welding. The joint design and welding conditions are shown in Figure 3 and Table 2, respectively.

  It is important to note that cathodic cleaning of the aluminum base metal and filler metal surfaces occurred when welding was done with argon shielding and reverse-polarity direct current. Cathodic cleaning of aluminum surfaces with a plasma arc was examined in the mid-1960s.[9] The removal of surface oxides in this manner minimizes the occurrence of porosity and other defects in aluminum welds.

*Also known as plasma-MIG welding.



a. Plasma-Arc Init...d by Pilot Arc



b. Plasma-Arc Initiated by GMA Arc

FIGURE 2. Sketches of Plasma-GMA Welding Systems(8)

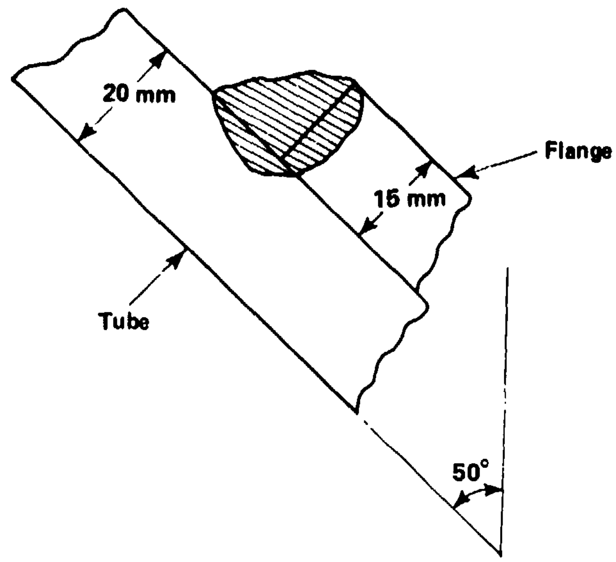


FIGURE 3. Cross Section of Aluminum Tube-To-Flange Joint(8)

TABLE 2. Plasma-GMA Conditions for Welding Aluminum Tube-To-Flange Joint(8)

Plasma arc current, a	270
Plasma arc voltage, v	24
GMA current, a	300
GMA voltage, v	29
Wire feed rate, ipm	40
Welding time, min	2.5
Plasma gas, cfh	21 (argon)
Shielding gas, cfh	69 (argon-helium)

- The plasma-GMA welding of copper, stainless steel, mild steel, and other base metals has been also studied.(10, 11) In each instance, the high deposition rates associated with this process contributed toward increased welding speeds and low defect levels.

Plasma-GMA welding in the rotating-arc mode is used for cladding and surfacing. With rotational transfer, filler metal can be deposited at very high rates with minimum penetration of the base metal substrate. Bead widths of 1 inch can be readily obtained without oscillation of the welding torch. With oscillation, beads as wide as 2 to 3 inches can be produced. Deposition rates well in excess of those obtainable by many other methods can be obtained with plasma-GMA surfacing. For example, a 3/8-inch-thick layer of a nickel-base alloy was deposited on carbon steel at 20 lb/hr. Postweld evaluation of the deposit showed minimum penetration of the base metal, no hardening along the fusion line, a fully austenitic microstructure, and no hot cracking. Even higher deposition rates of 44 lb/hr have been achieved in the surfacing of massive components for nuclear reactors.(12) In one instance, alloy steel tube sheets with diameters ranging from 40 to 80 inches were clad with a 0.4-inch-thick layer of austenitic stainless steel. Weld cladding was done in concentric circles at a deposition rate of 35 lb/hr; two layers were required to produce the required cladding thickness.

Plasma Surfacing with Metal Powders. Although the basic process for plasma-arc surfacing with metal powders was developed in the early 1960s, there is a renewed interest in this process because of the high-deposition rates that can be obtained with it. As indicated in Figure 4, this process uses a transferred plasma arc to produce melting of the base metal surface during the cladding operation.[13] Metal powder from a dispenser is metered into the plasma arc below the constricting nozzle. After entering the arc, the powder particles are heated and deposited on the molten surface to form a homogeneous deposit that is metallurgically bonded to the workpiece. Since only the base metal surface becomes molten during the cladding operation, dilution can be minimized by proper selection of the process variables. Metals that are available in powder form can be used for surfacing; however, for best results, the surfacing material should melt at a temperature below the melting point of the base metal.

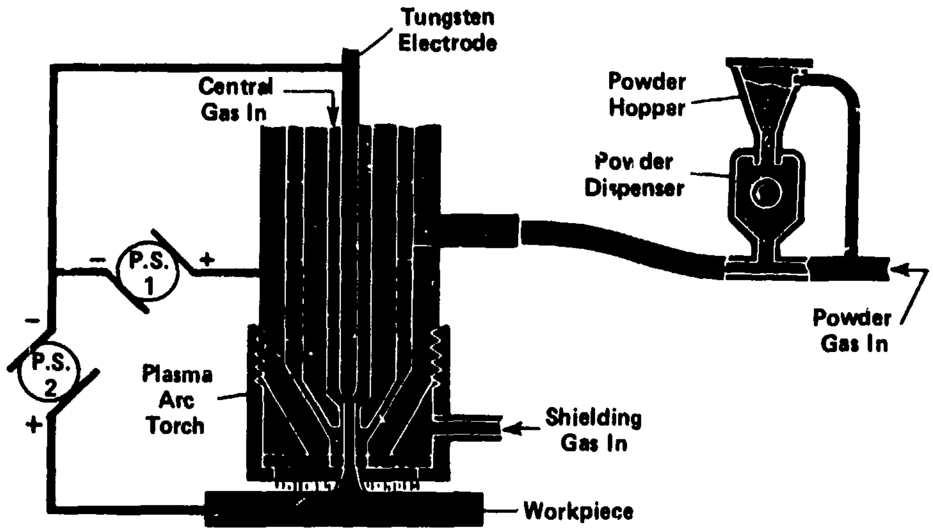


FIGURE 4. Sketch of Plasma Arc System with Powder Addition[13]

This process is of current interest because of the rate at which various metallic substrates can be clad with materials that resist oxidation, wear, corrosion, and other forms of attack, and as a result, improved surfacing equipment is being developed and marketed. This process has been used to surface sections of extruder screws with a cobalt-base alloy to improve the wear and abrasion resistance during the extrusion and ejection molding of plastics.[14] The time required for hardfacing was reduced 50 percent and material costs were reduced as well.

Microplasma-Arc Welding. Advances in equipment development have significantly extended the process capabilities of microplasma-arc welding. As its name implies, this is a low-current process designed for welding metal foil and thin sheet stock. Welding can be done at currents as low as 0.1 ampere; and upper current levels range as high as 25 to 50 amperes. In addition to the miniature plasma torch, the latest equipment includes a solid state power source designed for stable low-current operation. The power source features current upslope and downslope controls and includes means to pulse the welding current at frequencies ranging as high as 10,000 hertz. The process variables can be programmed to improve the quality and reproducibility of welding.

With current capabilities ranging from 0.1 to 25 amperes, this equipment can be used to produce welded joints in foil and sheet stock with thicknesses of 0.0004 to 0.60 inch; it can be also used to weld small-diameter wire. In production, it has been used to weld items such as bellows formed from thin sheet stock, wire mesh, expanded metal screen, sheet metal membranes, and thin-wall tubing.[15]

Submerged-Arc Welding

In single-electrode submerged-arc welding, the heat required for fusion is obtained from an arc established between the electrode and workpiece. A layer of granular, fusible flux provides shielding for the arc and molten weld metal. Filler metal is obtained from the electrode and sometimes from a supplementary filler metal addition. After the arc is initiated, melting of the base metal, filler metal, and flux occurs in the immediate vicinity of the arc. As melting progresses with the continued addition of filler metal and flux, the base metal and filler metal combine to form a pool of molten weld metal. Concurrently, the melted flux floats to the surface and forms a protective slag over the solidifying weld metal. In addition to providing the required shielding, the flux affects the cleanliness, composition, and properties of the weld metal, influences the arc characteristics, determines the appearance of the weld bead, and promotes slow cooling of the weld metal.

This process is used extensively for welding and cladding carbon steels, low alloy and alloy steels, stainless steels, and various nickel-base alloys. Because of the high heat inputs and high deposition rates associated with this process, it is best suited for the welding of plate, but sheet as thin as 1/8 inch can be welded at low current levels. Many process variations are available, most of which were developed to increase deposition rates: e.g., welding with multiple wire electrodes, welding with hot or cold wire additions, welding with strip electrodes, and welding with metal powder additions.

While this process is used mostly for welding ferrous metals and some nickel-base alloys, other metals can be welded in this manner if suitable fluxes are available. For example, titanium and titanium alloys have been submerged-arc welded in the Soviet Union for many years with special fluxes, and work has been undertaken here to develop such fluxes for similar applications.[16] Because the high reactivity of titanium precludes the use of oxide-base fluxes, efforts were directed toward the development of fluxes based on calcium fluoride with additions to control variables such as melting temperature and moisture pickup. Conclusions based on the results of this investigation are indicated below:

- Fused fluxes were superior to blended fluxes in terms of atmospheric protection and hydration rate.
- Fused CaF_2 fluxes provided adequate protection and fluxing for the groove welding of titanium alloys. Auxiliary shielding with argon resulted in the production of joints with somewhat lower yield strength and somewhat improved fracture toughness.

- Submerged-arc welding with fused CaF_2-base fluxes produced joints with intermediate strength-toughness characteristics.

While submerged-arc welding is an old established process, it has enjoyed a revival of sorts in recent years because there are few health and safety problems associated with its use. Fume and gas levels are negligible and radiation is nonexistent because the arc and pool of molten weld metal are covered with a layer of melted flux as well as a protective slag. Noise and heat levels are low to moderate and any discomfort can be alleviated with protective devices and clothing. As a result of these considerations and the technical excellence of the process, submerged-arc welding is being actively considered for many applications instead of the gas-shielded arc welding processes.

Two process developments which promise increased productivity in cladding and surfacing operations are reviewed in the following sections.

Welding With Strip Electrodes. As indicated in Figure 5, submerged-arc strip welding closely resembles the single-wire version of this process except that the electrode is a thin strip instead of a wire. The strip dimensions vary widely in accordance with the cladding or overlaying application. Typical widths and thicknesses range from 1 to 5 inches and 0.020 to 0.040 inch, respectively. Some advantages of strip overlay welding are indicated by the following:

- Wide overlays can be deposited and built up to the required thickness at rates two to five times faster than those obtained with other processes. Deposition rates are well in excess of 30 lb/hr.
- Multiple arcing between the edge of the strip and the workpiece occurs during overlaying. As a result, high-intensity arc forces at a given point are eliminated and penetration as well as dilution by the base metal are minimized.
- The transition zone between the overlay material and the base metal is only a few thousandths of an inch thick.
- The smooth surface of the overlays eliminates or minimizes the need for finish machining. Repair and rework operations are also minimized because the overlays are relatively defect-free.

Submerged-arc strip welding was developed in Europe for the cladding or overlaying of large components, such as tubesheets, shafts, rolls, nozzles, chemical and nuclear vessels, etc. Despite its high productivity and cost-effectiveness, this process has not received the acceptance in this country that it has in Europe; however, it is being aggressively marketed in the United States at present. As is the case with all surfacing operations, this process is used to clad a base component with a material that provides resistance to oxidation, corrosion, wear, abrasion, or erosion. Depending on the size of the area to be surfaced, overlaying operations can be exceedingly time-consuming, and any method that reduces production time should be considered seriously. Table 3 provides an indication of the savings in time that can be realized with strip overlay welding.[17]

Data on typical surfacing applications are available to guide the prospective user of this process. For example, studies have been undertaken to select the consumables and establish the operating conditions for surfacing a carbon steel substrate with one of several candidate

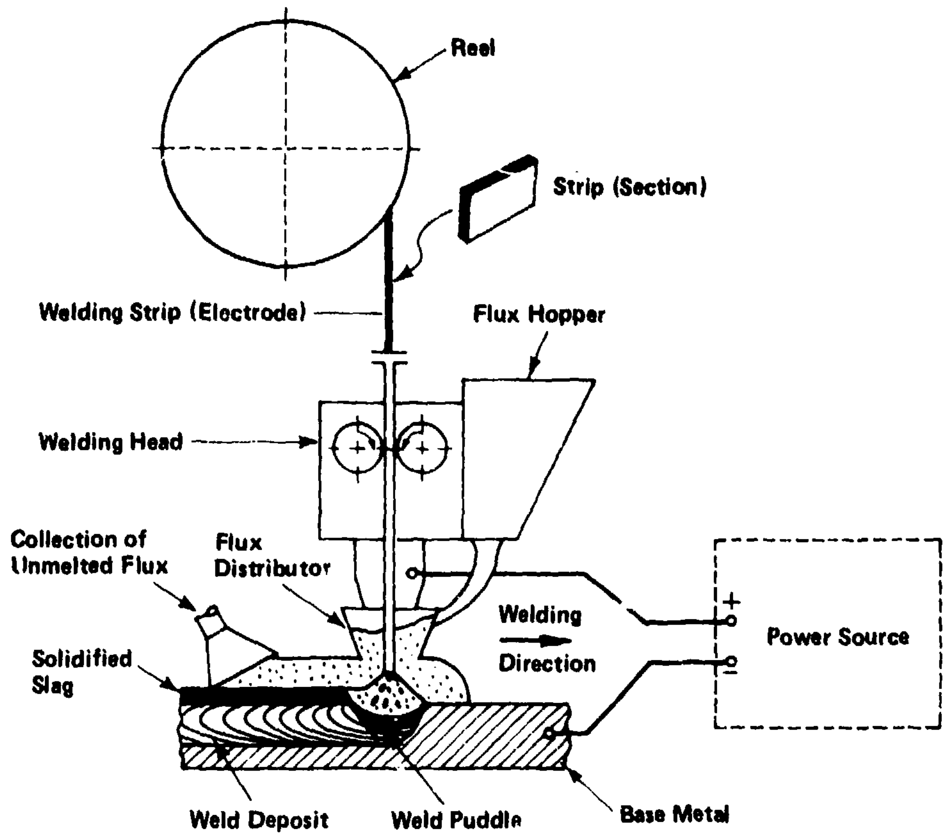


FIGURE 5. Submerged-Arc Strip Welding(17)

TABLE 3. Production Capabilities of Submerged-Arc Strip Welding(17)

Component	Component Dimensions, in.	Overlay Thickness, in.	Overlay Material	Welding Time, hr Strip Overlay	Welding Time, hr Other Method
Tubesheet	60 in. diam x 4 in. thick	1/4	304L SS	8	34 (1-wire SAW[a])
Tubesheet	48 in. diam x 2-1/2 in. thick	3/8	ERNiCr-3	8	29 (1-wire SAW)
Tubesheet	56 in. diam x 11 in. thick	1/2	304L SS	12.5	25 (2-wire SAW)
Tubesheet	80 in. diam x 2-1/2 in. thick	5/8	ERNiCu-7	31	61 (2-wire SAW)
Tubesheet	50 in. diam x 4 in. thick	1/4	347 SS	5.5	19 (1-wire GMA[a])
Vessel	120 in. diam x 120 in. long x 4 in thick	1/4	316L SS	129	220 (2-wire SAW)
Vessel	76 in. diam x 96 in. long x 4 in thick	3/16	ERNiCr-3	75	278 (1-wire SAW)
Shaft	15 in. diam x 60 in. long	3/8	ERNiCu-7	11	46 (1-wire SAW)

(a) SAW means submerged-arc welding; GMA means gas metal-arc welding.

stainless steels.[18] In each instance, the Schaeffler diagram was used to select the composition of the strip electrode that was needed to produce an overlay with the required composition. Compatible fluxes were also selected for use with each electrode and the deposition sequence was established along with the operating conditions needed to control dilution of the overlay by base metal constituents. Studies of the composition gradient across the overlay were conducted and the effects of stress-relief heat treatment on the microstructures in the transition and heat-affected zones were examined. Typical conditions for welding with various sized strip electrodes are shown in Table 4.

TABLE 4. Submerged-Arc Wide Strip Welding with 308L SS Strip[18]

Strip Dimensions, in.	Current, a	Voltage, v	Welding Speed, ipm	Deposit Thickness, in.	Deposition Rate, lb/hr	Dilution, percent
2.4 x 0.020	750	28	4.7	0.160	33.0	15
	750	28	6.3	0.125	33.0	23
	1,050	28	5.1	0.208	44.0	18
	1,200	28	7.8	0.170	50.6	20
	1,350	29	9.1	0.197	57.2	22
3.5 x 0.020	1,200	28	5.1	0.197	50.6	15
4.7 x 0.020	1,400	30	4.0	0.177	59.4	10
	1,550	28	4.1	0.197	66.0	15
	1,800	23	4.0	0.197	72.6	22
7.1 x 0.020	1,850	27	3.5	0.177	68.2	8

The manner in which the welding conditions, dilution rate, and metal transfer characteristics are affected by the type of flux used in stainless steel strip welding has been studied by Zentner.[19] Also, the use of strip electrodes for welding vee-groove joints has been explored by Franz.[20]

Welding With Metal Powder Additions. Submerged-arc welding with metal powder additions dates back to the late 1960s; however, there is renewed interest in this process because it also represents a relatively inexpensive means to improve productivity by increasing the deposition rate during welding and cladding operations.[21] As indicated in Figure 6, this process is identical to conventional submerged-arc welding with the exception that the equipment incorporates a hopper and metering device to add controlled amounts of metal powder immediately ahead of the welding electrode. The heat provided by the arc melts the base metal, the filler metal, and the metal powder to form a large pool of molten weld metal that is protected from atmospheric contamination by a layer of melted flux and slag. While the concept of using metal powder additions to increase deposition rates is not restricted to submerged-arc welding, maximum benefits can he best achieved with a process having an inherent capability of depositing metal at high rates. This process can be used with equal facility for welding and cladding; however, its cost-effectiveness is most evident in cladding operations. Among the advantages of this process are the following:

- In comparison with single-wire submerged-arc welding, deposition rates can be increased two to three times at given current levels with powder additions. This capability is reflected by the data shown in Figure 7. Deposition rates range from 20 to 60 lb/hr and more.
- Wide weld beads can be deposited during overlaying operations and the bead width can be increased substantially by oscillation of the welding head.
- The metal powder chemistry can be varied to obtain overlays with properties corresponding to the requirements of the application. Alloy metal powders can be used, or alloys can be produced by the fusion of blended powders composed of the alloy constitutents.
- Flux consumption can be reduced appreciably.

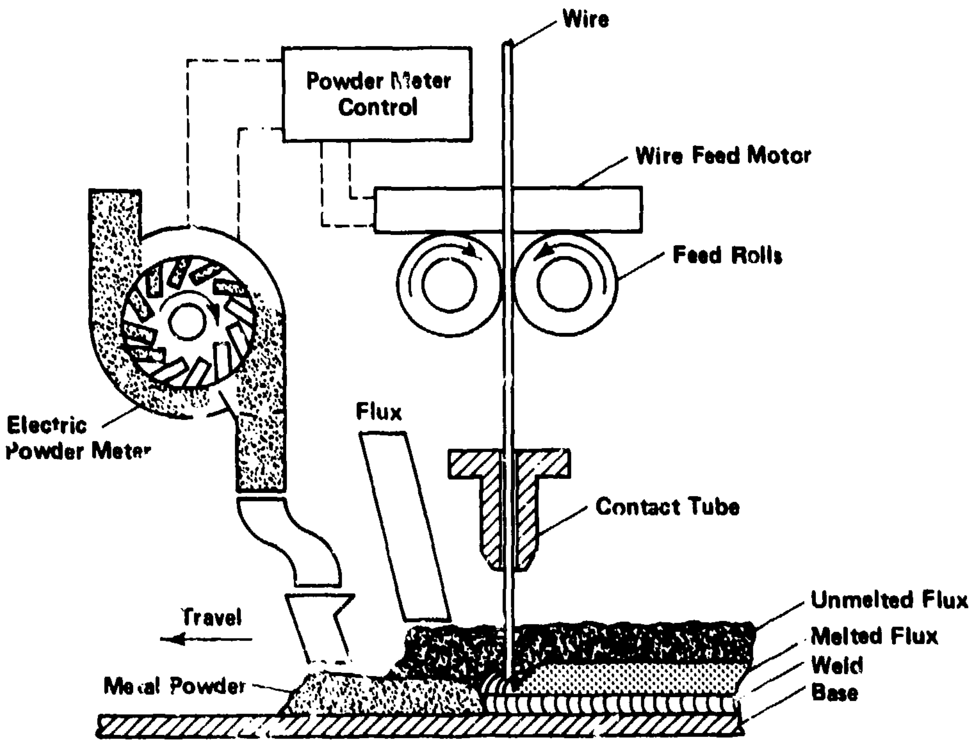


FIGURE 6. Submerged-Arc Welding With Powder Additions[21]

The use of metal powder additions in the multiwire submerged-arc welding of square-butt, vee-groove, and fillet joints in structural steels has been investigated.[22] With two wires arranged in tandem, the additional filler metal provided by the metal powder produced a 67 percent increase in the deposition rate. Much greater increases in the deposition rate could be also obtained, since the use of metal powder additions permitted much higher welding currents; rates as high as 190 lb/hr were achieved during the welding of heavy joints in the flat position. Since welding was accomplished in fewer passes with metal powder additions, the

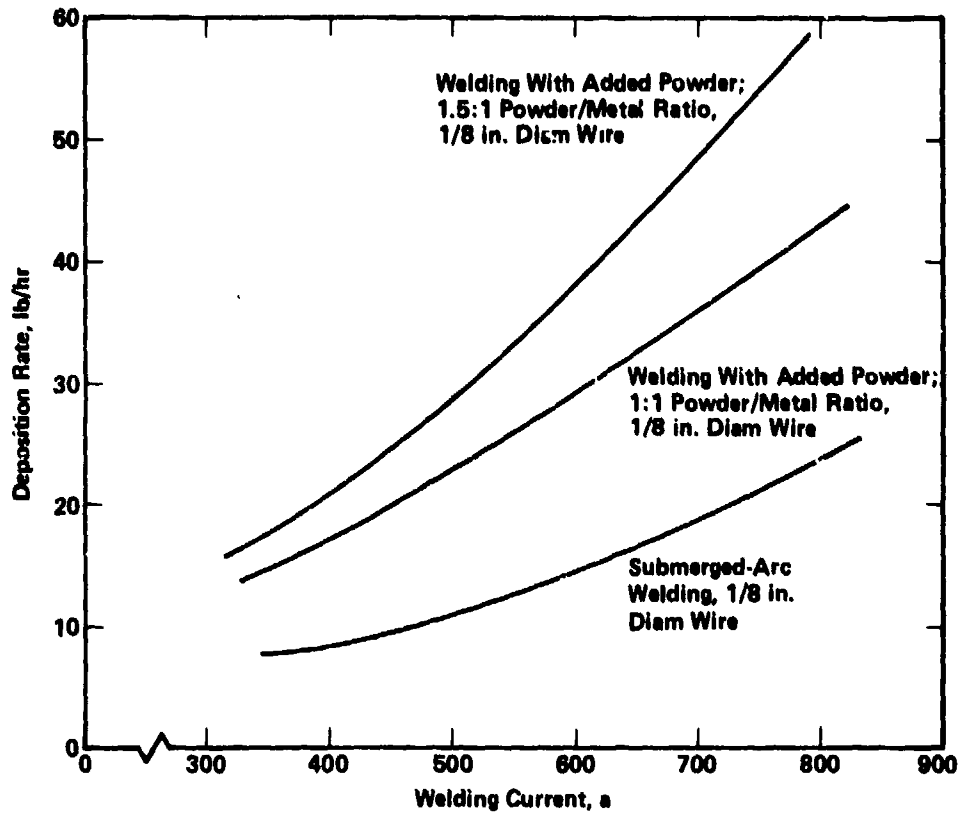


FIGURE 7. Effect of Powder Additions on Deposition Characteristics of Single Electrode Submerged-Arc Welding[21]

distortion of structural members during welding was minimized. The properties of joints produced in this manner consistently exceeded the requirements of various regulatory agencies.

Electron-Beam Welding

In this method of welding, the heat required for fusion is provided by a focused beam of high-velocity electrons which impinges on the workpieces. Upon impact, the kinetic energy of the beam is transformed to heat. An electron gun is used to generate the electrons, focus them into a beam, and accelerate them to very high velocities. As the beam of electrons leaves the gun, it diverges and must be refocused with magnetic deflection coils to form a spot on the workpiece. The amount of heat produced in the workpiece depends on the beam current, the accelerating voltage, the beam spot size, and the rate at which the beam is moved along the joint.

Electron-beam welding equipment is classified in accordance with the voltage used to accelerate the electrons and the degree of vacuum required for welding. While the distinction between low voltage and high voltage equipment is not clear cut, it is generally agreed that accelerating voltages up to 60 kv are used in low-voltage units and accelerating voltages of 60 to 175 kv are used in high-voltage units. The magnitude of the accelerating voltage is important, because it affects the amount of penetration and the width of the welded joint and its heat-affected zone. Equipment is available for welding in a high vacuum, in a medium vacuum, or in the open at atmospheric pressure (Figure 8).[23] However, regardless of the pressure at which welding is done, the electron gun must function in a vacuum of 10^{-4} torr or less. Equipment characteristics are reviewed briefly:

- High-vacuum welding is done in a chamber evacuated to a pressure of 10^{-3} to 10^{-6} torr. Joints with the greatest depth-to-width ratios can be produced with this equipment, and metals whose properties are adversely affected by gaseous contaminants can be readily welded. Production rates are relatively slow because of the time required to load and evacuate the chamber; however, such rates can be increased with larger pumping systems, carousel fixturing, etc.
- Medium vacuum welding is done in a chamber that is evacuated to a pressure of 10^{-3} to 25 torr. Production rates can be increased with this equipment, since less time is needed to evacuate the welding chamber. However, as indicated in Figure 9, the input power must be increased to achieve the same penetration that can be achieved with high-vacuum equipment.[24] If reactive and refractory metals are welded under medium-vacuum conditions, the presence of gaseous contaminants may have an adverse influence on joint properties and characteristics.
- Nonvacuum welding is done in the open at atmospheric pressure so production rates can be increased and costs can be decreased. In addition, the size of the weldment is limited only by practical considerations. However, to obtain these advantages, a penalty must be paid in the form of reduced penetration, reduced weld bead depth-to-width ratios, increased power requirements, and decreased gun-to-work distances. Most ferrous and nonferrous metals can be welded in this manner. Gas shielding is used to protect the molten weld metal from atmospheric contamination, and filler metal is added as required.

Further information on the capabilities and limitations of electron-beam welding can be obtained from the technical literature.

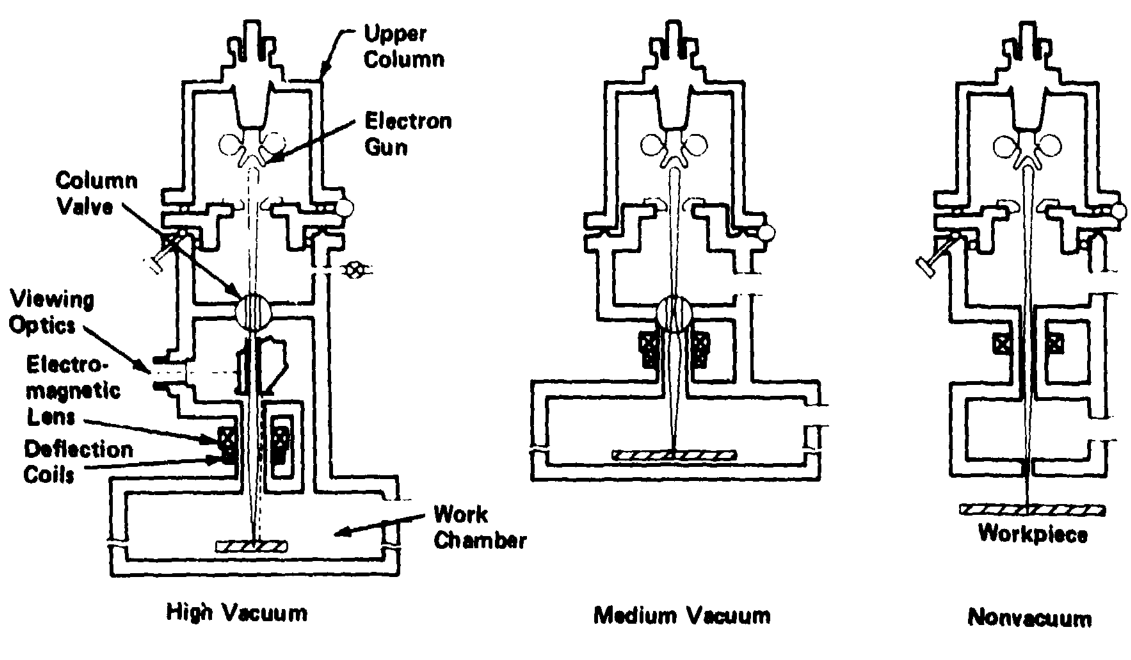


FIGURE 8. Sketches of Basic Modes of Electron-Beam Welding[23]

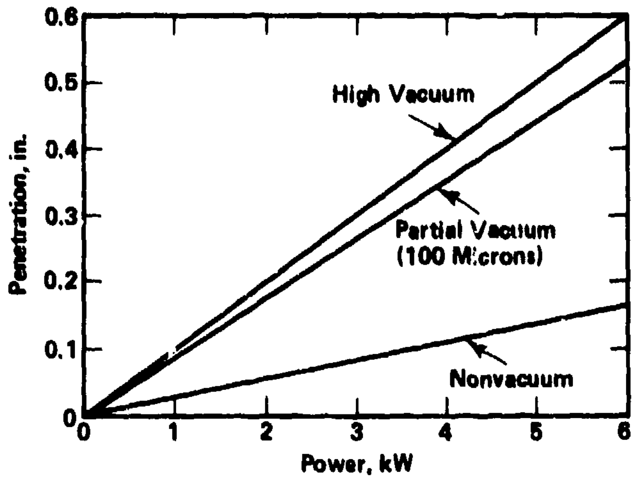


FIGURE 9. Power Versus Penetration Characteristics During the Electron-Beam Welding of Steel(24)

High- and Medium-Vacuum Welding. Although the basic electron-beam welding process is well established, recent innovations have extended its capabilities and improved its performance. For example, electronic systems have been developed to deflect the beam in accordance with paths designed to achieve the following specified welding objectives: increasing penetration and weld depth-to-width ratios, improving bead surface contour, reducing weld metal dropthrough, eliminating pipe cavities, etc.[25] With this equipment, the choice of beam deflection modes for making circular and linear welded joints is almost unlimited. Other process improvements include a beam current controller and a real-time seam tracking device.

Filler metal is not usually added to the joint during normal electron-beam welding, and the choice of available joint designs is very limited as a result. While this restriction is not important in many instances, there are occasions when it would be advisable to use a vee-groove joint design to achieve a specific welding objective or to eliminate defects (porosity, cold shuts, variations in penetration, etc.) that sometimes occur during autogenous welding. Such a joint design requires the addition of a compatible filler metal. A wire feeder and positioner with components designed for operation in a high vacuum have been developed for making narrow groove welds.[26] This equipment has three axes of motion and can be programmed for multipass electron-beam welding operations. The parameters for welding two aluminum alloys, a high-strength steel, and uranium along with the dimensions of the vee-groove joints are shown in Tables 5a and 5b. The tensile and elongation properties of these joints were excellent and defect levels were very low.

Nonvacuum Welding. The technology of nonvacuum electron-beam welding has progressed steadily in recent years, and this process is being used by various segments of industry to fabricate weldments on a routine basis. Within reason, the size and complexity of the weldment are immaterial as long as the joints can be properly fixtured and positioned for welding. Joints are usually welded without filler metal; however, joints that require added filler metal can be welded also. The ability to accomplish welding without regard to the constraints presented by a vacuum chamber has broadened the opportunities for electron-beam welding appreciably. As a result, this process can be used with equal facility to weld parts for automobiles and critical components for aircraft.

TABLE 5a. Parameters for Multipass Electron-Beam Welding of Narrow-Groove Joints(26)

Material	Weld Pass	Filler Wire Diam, in.	Parameter[a] Voltage, kv	Current, ma	Focus, ma	Speed, ipm	Wire Feed Rate, ipm	Filler Metal
6061-T6 Al	1	0.030	75	9	410	18	18	ER 4043
	2	0.030	75	9	420	18	30	ER 4043
	3	0.030	75	9	430	12	30	ER 4043
	4	0.030	75	9	430	12	30	ER 4043
5083 Al	1	–	75	5	430	20	–	Autogenous
	2	0.030	75	8	455	20	20	ER 5356
	3	0.030	75	8	455	14	30	ER 5356
	4	0.030	75	8	455	14	30	ER 5356
	5	0.030	75	8	455	14	30	ER 5356
	6	0.030	75	8	455	14	30	ER 5356
HP 9-4-20 Stl	1	–	100	2.0	442	15	–	Autogenous
	2	0.030	100	3.5	475	15	15	HP 9-4-25
	3	0.030	100	5.0	475	15	35	HP 9-4-25
	4	0.030	100	5.0	475	15	35	HP 9-4-25
Uranium	1	0.030	107	4	460	20	–	Autogenous
	2	0.030	107	10	480	20	20	Uranium
	3	0.030	107	10	490	20	20	Uranium
	4	0.030	107	10	495	20	20	Uranium
	5	0.030	107	10	485	20	20	Uranium
	6	0.030	107	10	485	20	20	Uranium
	7	0.030	107	10	485	20	20	Uranium
	8	0.030	107	10	490	20	20	Uranium
	9	0.030	107	15	485	0	40	Uranium
	10	0.030	107	15	490	20	40	Uranium
	11	0.030	107	15	490	20	40	Uranium

(a) Sharp focus at root of joint for 6061 Al, 5083 Al, HP 9-4-20 Stl, and uranium was 385, 385, 427, and 446 ma in the same order.

TABLE 5b. Narrow-Groove Joint Geometries

Material	Thickness, in.	Bevel Angle, deg	Root Radius, deg	Root Face, in.	Root Gap, in.
6061-T6 Al	0.213	7.5	0.030	0.040	None
5083 Al	0.213	7.5	0.030	0.040	None
HP 9-4-20 Stl	0.100	10.0	0.020	0.025	None
Uranium	0.500	5.0	0.030	0.030	None

The economics of nonvacuum electron-beam welding favor the use of this process by the automotive industry. For example, this process has been used to join the component parts of a die-cast aluminum manifold for 6-cylinder engines.[27] The total length of the joint was 75 inches and welding was accomplished in 22 seconds, exclusive of handling time. Welding speeds ranged from 150 ipm in tightly radiused corners to 450 ipm in straight sections of the manifold; tiller-metal additions were not needed. This process has been also used to weld various assemblies for automotive transmissions (e.g., annulus gear assemblies) at rates up to 600 parts per hour.[28] Blanks for automotive frame components have been produced in large quantities in a high-voltage nonvacuum facility that has a potential production rate of 800 blanks per hour.[29] The two-piece blanks were made from rimmed steel sheet stock and were formed to the proper contour after welding. The relationship between base metal thickness and welding speed is shown in Figure 10 for various beam orifice-to-work distances.

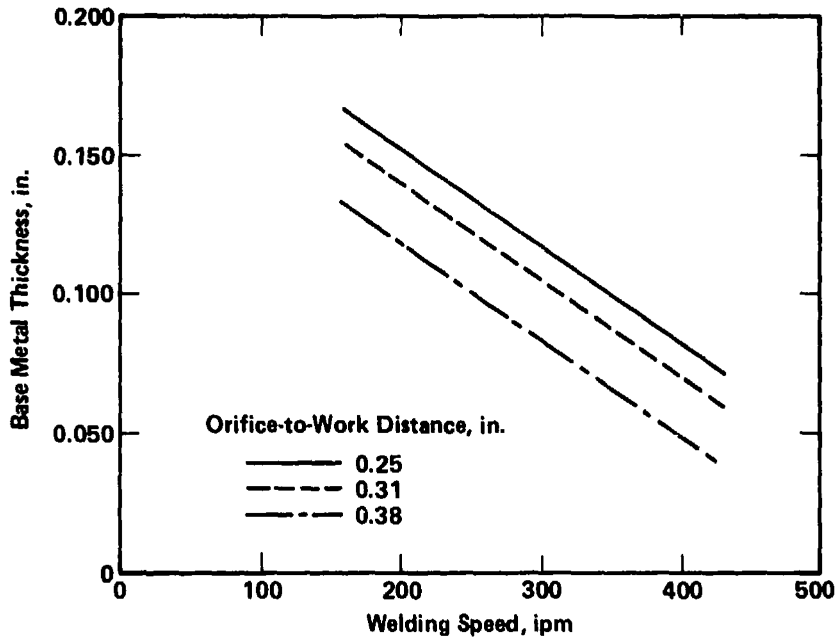


FIGURE 10. Parameters for Nonvacuum Electron-Beam Welding of Rimmed Steel Showing Effect of Orifice-To-Work Distance on Welding Speed[28]

(Beam current: 70 ma; beam voltage: 175 kv)

Process versatility has been also demonstrated by the fabrication of gas turbine components.[30] Following studies to establish parameters for welding various aerospace base metal, a turbine wheel comprised of a ring of Udimet 500 blades and an A-286 hub was fabricated. Spin test results indicated that failure occurred at a stress level corresponding to the strength of the weaker joint member.

Computer numerical control has increased the capabilities of electron-beam welding. All sequencing operations and the welding parameters can be controlled and major machine functions are on a closed loop feedback system. With this equipment, setup times can be reduced and on-line programming activities can be conducted.

Laser-Beam Welding

The heat required for laser-beam welding is provided by a high-energy beam of radiation that impinges on the workpieces to produce melting and fusion. The laser is a device that converts one source of energy (electrical, chemical, optical, etc.) to a beam of electromagnetic radiation at frequencies in the infrared, visible, or ultraviolet spectrum. Energy conversion is facilitated by the use of certain solids, liquids, or gases which emit radiation when they are excited on the atomic or molecular scale by special techniques. The radiation is monochromatic (single wave length) and coherent (all waves in phase). Because the beam is coherent, it can be readily focused by transmitting or reflecting optics to provide the high-energy density required for welding. The laser beam can be used to weld metals that are considered weldable by other fusion welding methods.

While the manner in which lasing occurs is beyond the scope of this report the major characteristics of lasers available for welding are discussed in the following sections and complete data are available in the technical literature on lasers.

- Solid-state lasers function with glasses or single crystals that are doped with transition elements (e.g., chromium in ruby crystals) or rate-earth elements (e.g., neodymium in glass or yttrium aluminum garnet crystals). The outer-shell electrons in the atoms of the transition or rare-earth elements can be selectively excited to a higher-energy state upon exposure to a source of intense-incoherent optical radiation, such as white light produced by an electronic flash lamp. When the electrons revert to their normal energy state, a quantum of energy is released at each step on the way. Lasing occurs if energy is released in the form of a quantum of electromagnetic radiation, the wavelength of which is determined by the fluorescense spectrum of the rare-earth or transition element. The essential details of a solid-state laser are shown in Figure 11; the mirrors used to amplify the laser output and produce a beam of nearly monochromatic radiation are also indicated.[23]

  The output of a solid-state laser is pulsed or continuous, depending on the laser material and the source of incoherent energy. The power ratings of pulsed units range from a few to several hundred watts; continuous wave solid-state lasers with outputs up to 2000 watts are also available. The penetration characteristics of pulsed lasers are shown in Figure 12.

- In gas lasers, gaseous molecules are vibrationally excited to a higher-energy level in an electric discharge. Although many gases can be used as the lasing medium, CO_2 is most commonly used in industrial lasers that are designed for welding; nitrogen is usually added to improve the excitation efficiency of a CO_2 laser. Transition from a higher vibrational-energy state to a lower-energy state occurs with the emission of a quantum or photon of electromagnetic radiation. Totally reflecting and partially transmitting mirrors are used to amplify the laser output and produce a coherent beam of nearly monochromatic radiation whose wavelength depends on the lasing medium. The essential features of a gas laser are shown in Figure 13.[23]

While pulsed or continuous wave gas lasers are available, lasers with a continuous output are usually used for welding. In the continuous output mode, CO_2 lasers with ratings up to 20,000 watts or more are available; pulsed units are rated up to about 1500 watts. Penetration as a function of laser power and welding speed are shown in Figure 14.[23]

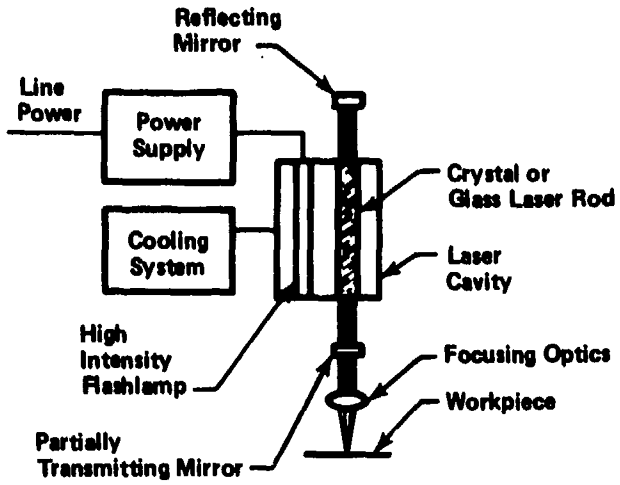


FIGURE 11. Elements of Solid-State Laser System(23)

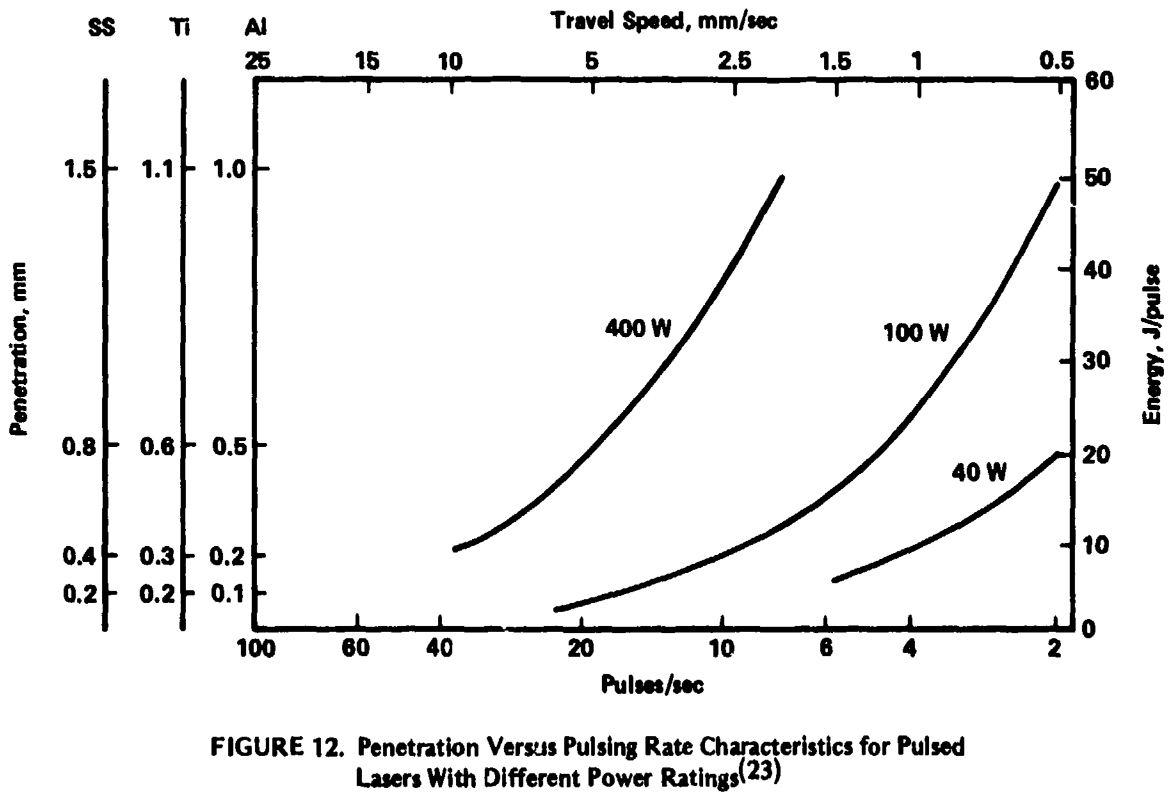


FIGURE 12. Penetration Versus Pulsing Rate Characteristics for Pulsed Lasers With Different Power Ratings(23)

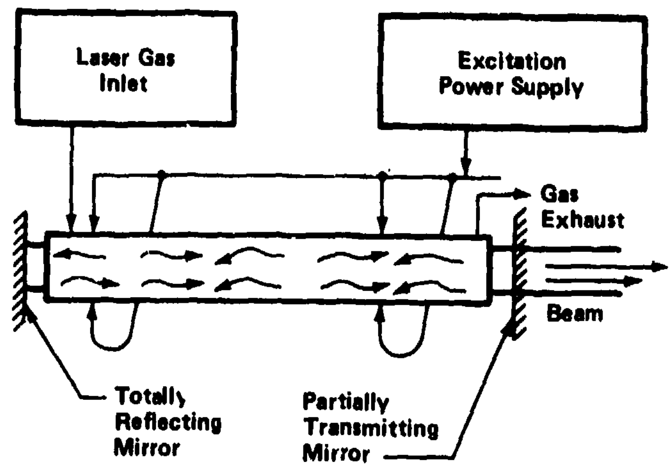


FIGURE 13. Elements of Basic Gas Laser System(23)

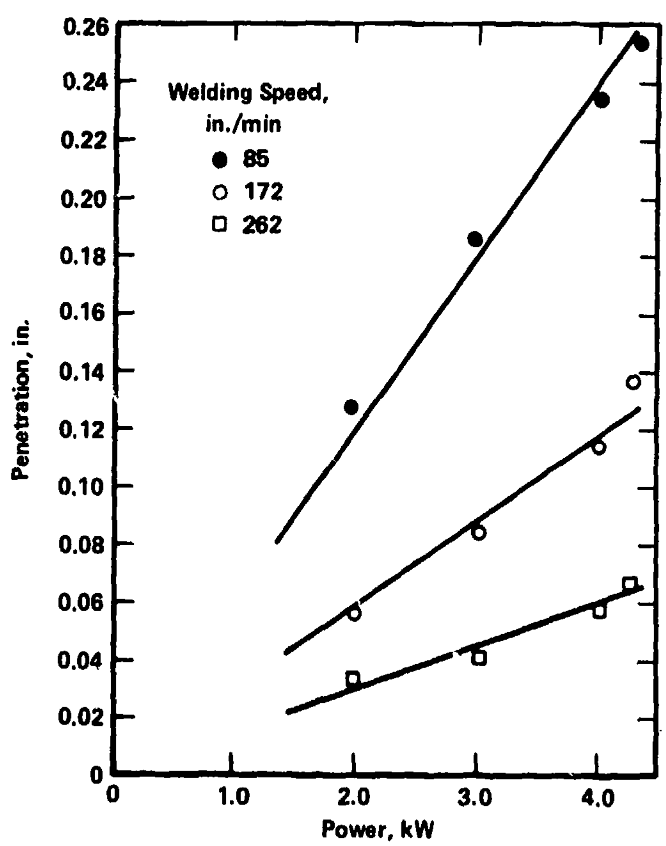


FIGURE 14. Penetration Versus Power Characteristics of CO_2 Laser in Rimmed Steel at Different Welding Speeds(23)

To produce the power densities required for welding, the laser beam must be optically focused to a very small diameter. Focusing is usually done with fixed-focus optics, and the workpieces must be positioned within the depth-of-focus of the optical system. Laser beam welds can be produced by (1) the melt-in or conduction-limited mode, or (2) the keyhole or deep penetration mode. In the melt-in mode, the energy of the impinging laser beam is absorbed at the surface of the workpiece; heating of the subsurface regions of the workpiece occurs by conduction from the heated surface. Melt-in welding to produce joints with relatively low depth-to-width ratios is usually done with pulsed or continuous wave lasers rated at 1000 watts or less. In the second mode, local vaporization of metal at the surface of the workpiece is produced by a high-energy laser beam. As the vaporization process progresses, a cavity or keyhole surrounded by molten metal is formed; the keyhole moves along the joint with the progressively advancing laser beam. Surface tension forces support the molten metal and close the keyhole behind the moving beam. Deep penetration welding is done with high-power pulsed or continuous wave lasers to produce joints with high depth-to-width ratios.

Joint designs for the autogenous welding of sheet and plate stock are shown in Figure 15.[31] These designs and the fitup requirements are similar to those used in electron-beam welding. Inert gas shielding is used to protect the molten weld metal from contamination by atmospheric constituents. Gas shielding is also needed to suppress the plasma formed by ionized metal vapors. Unless suppressed, the plasma absorbs the energy of the laser beam and reduces the heat input to the workpiece.

Several laser-beam welding applications are cited in the following sections to demonstrate the capabilities and versatility of this joining process.

Pulsed Laser Beam Welding. Pulsed lasers can be used to join wires together with conventional joint configurations: butt, lap, tee, and crossed wires. Sheet members can be joined together with individual spot welds or with seam welds comprised of a series of closely overlapping spot welds. These lasers are particularly well suited to electronic applications (fabrication of lead-throughs, attachment of contacts, hermetic sealing of modules, etc.) and other small-parts applications (sealing of battery cans, welding of bellows, fabrication of heart pacer modules, joining of foils, etc.). For example, a pulsed ruby laser has been used to simulate the attachment of a nuclear reactor fuel-pin bundle to a tube sheet.[32] In the course of this investigation, parameters were developed to weld an assembly of closely packed 0.230-inch-diameter Type 316 stainless steel tubes to a small tubesheet made from Type 304 stainless steel; the limited spacing between the tubes precluded welding by other fusion methods. The circumferential joints consisted of a series of overlapped spot welds made with the laser.

Many dissimilar-metal combinations can be successfully welded with the laser; however, it is not a cure-all for all applications. For example, a ruby laser was used to produce butt welds between small sections of 1/16-inch-thick titanium and nickel sheet stock. Laser beam butt welds were made in various ways: a single pass of overlapping spot welds on both sides of the joint, and multipasses of overlapping spot welds on both sides of the joint. Regardless of the welding procedure, cracking was observed in the fusion zone. Cracking apparently resulted from the formation of one or more of the brittle intermetallic compounds that exist in the Ti-Ni alloy system.[33]

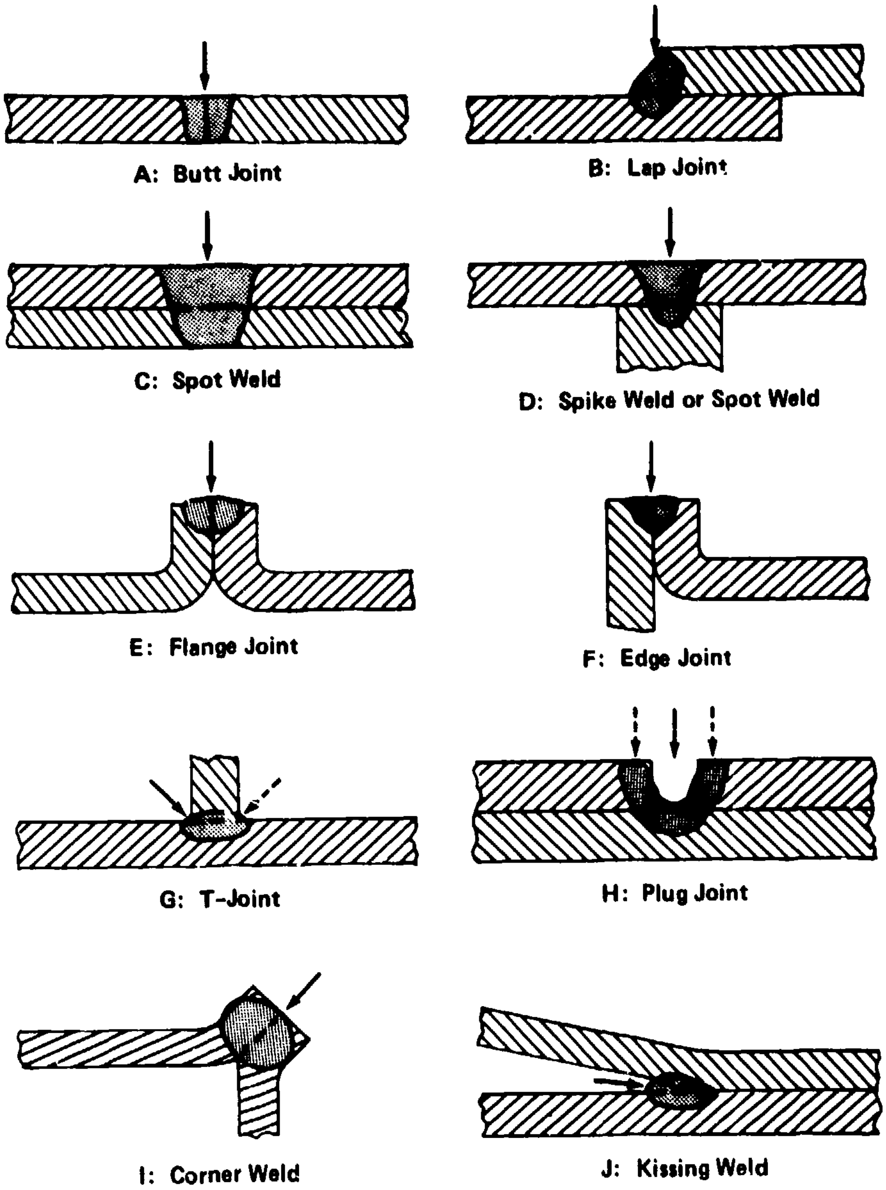


FIGURE 15. Joint Designs for Laser Beam Welds in Sheet Metal[31]

(Arrow shows direction of laser beam)

The ability to control the focus of the laser beam while delivering short pulses of energy has stimulated research on the use of this device for brazing application where it is not desirable to heat the entire workpiece to the temperatures required to produce melting and flow of the filler metal (e.g., when brazing must be done near heat-sensitive components, near glass-to-metal seals, near adhesive-bonded joints, etc.).[34] Two neodymium-doped yttrium-aluminum-garnet (YAG) lasers, a ruby laser, and a CO_2 laser were evaluated during the production of fillet brazes on tee specimens. An Nd:YAG pulsed laser rated at 50 watts provided the best combination of heat input control and response with a defocused beam which was allowed to traverse the joint until brazing was accomplished. The conditions for brazing a series of similar and dissimilar metal tee specimens are shown in Table 6a; the filler metals are shown in Table 6b. Gas shielding was used to protect the joint area from oxidation. Laser-brazed joints possessed excellent characteristics and the microhardnesses of the joints were somewhat higher than those of furnace-brazed joints.

Other applications of pulsed lasers are cited in the literature.[35,36]

Continuous-Wave Laser Beam Welding. The continuous-wave laser beam can be used to produce conduction-limited and keyhole welds in much the same manner as the electron beam which it so closely resembles. Low-power lasers rated at 1000 watts or less are used for welding sheet metal. Sheet as well as plate can be welded with high-power units rated at 15,000 watts or more. In the keyhole mode of operation, joints with high depth-to-width ratios can be produced in plate stock with a maximum thickness of about 3/4 inch in one pass; thicker plate can be welded in two passes, one from each side of the joint. With constant welding speed, penetration is largely a function of input power. However, it is also affected by the physical and metallurgical characteristics of the metals being welded.

In a study designed to demonstrate the welding capabilities of a 5000-watt continuous-wave CO_2 laser, joints in rimmed steel sheet and plate were welded at rates ranging from 300 ipm in a 0.060-inch-thick sheet to 10 ipm in a 0.400-inch-thick plate.[37] The joint designs used in this investigation are shown in Figure 16 and weld bead penetration as a function of welding speed at three power levels is shown in Figure 17.

Additional data on the capabilities of high-power CO_2 lasers are provided by the results of a recent Soviet investigation.[38] Low-alloy steel plate in thicknesses of 0.600 and 0.800 inch was welded in two passes at 65 and 43 ipm, respectively; the input power in both instances was 25,000 watts. The mechanical properties of these joints were equal to or better than those of joints welded by other fusion welding methods. Two-pass welds in a high-strength titanium alloy base metal were also made using the same input power conditions. Welding speeds ranged from 108 ipm for a 0.520-inch-thick plate to 62 ipm for a 0.800-inch-thick plate. The mechanical properties of these joints were almost equal to those of the parent metal.

Research has also been undertaken to examine the laser as a means to overcome the problems in thermal asymmetry that are sometimes encountered in welding thin metal sections to thick ones (e.g., the welding of thin-wall tubes to massive tubesheets).[39] In the course of this investigation, face-to-face butt welds between a 0.040-inch-thick titanium sheet and a 0.500-inch-thick titanium plate were produced at 59 and 95 ipm with power inputs of 1000 and 2000 watts, respectively.

TABLE 6a. Pulsed Laser Conditions For Brazing(34)

Specimen Number	Joint Type	Combination Type	Side No. 1[a] Alloy	Side No. 1[a] Thickness, in.	Side No. 2[a] Alloy	Side No. 2[a] Thickness, in.	Brazing Filler Metal[b][f] AWS Classification	Brazing Filler Metal[b][f] Form	Total Pulse Energy, J	Measured Beam Spot Diameter, mm	Laser Beam Pulse Characteristics[g] Total Pulse Width, ms	Effective Pulse Width, ms	Pulse Peak Power, kW	Energy Density, J/cm^2	Power Density, W/cm^2
1	90 Deg Tee	Similar	304 SS	0.005	304 SS	0.005	BAg-8	Powder(c)	7.3	1.09	10	8.5	0.86	0.782×10^{3}	9.22×10^{4}
2	90 Deg Tee	Similar	316 SS	0.005	316 SS	0.005	BNi-2	Powder(d)(e)	5.2	1.07	10	8.5	0.61	0.578×10^{3}	6.79×10^{4}
3	90 Deg Tee	Similar	Aluminum	0.0125	Aluminum	0.0125	BAlSi-2	Foil(c)	15.0	0.89	10	8.5	1.76	2.412×10^{3}	28.30×10^{4}
4	90 Deg Tee	Similar	Molybdenum	0.005	Molybdenum	0.005	BCu-1	Foil(d)	8.7	0.76	10	8.5	1.02	1.921×10^{3}	22.52×10^{4}
5	90 Deg Tee	Similar	302 SS	0.001	302 SS	0.001	BAg-1	Powder(c)	0.23	0.31	8	6.8	0.03	0.305×10^{3}	3.98×10^{4}
6	90 Deg Tee	Dissimilar	316 SS	0.005	Titanium	0.010	BAg-8	Powder(d)(e)	7.6	1.14	10	8.5	0.89	0.745×10^{3}	8.73×10^{4}
7	90 Deg Tee	Dissimilar	Monel	0.010	316 SS	0.004	BAg-6	Powder(c)	4.5	0.74	10	8.5	0.52	1.047×10^{3}	12.33×10^{4}
8	90 Deg Tee	Dissimilar	Nickel	0.010	Kovar	0.010	BAu-4	Powder(d)	5.3	0.76	10	8.5	0.62	1.170×10^{3}	13.80×10^{4}
9	90 Deg Tee	Dissimilar	Copper	0.010	Nickel	0.010	BAg-18	Powder(c)	14.7	1.09	10	8.5	1.73	1.576×10^{3}	18.54×10^{4}
10	90 Deg Tee	Dissimilar	Nickel	0.010	Ingot Iron	0.010	BCu-1	Foil(d)	6.8	0.76	10	8.5	0.80	1.501×10^{3}	17.86×10^{4}
11	90 Deg Tee	Dissimilar	302 SS	0.001	1020 Steel	0.001	BAg-8	Powder(c)	0.80	0.31	8	6.8	0.12	1.061×10^{3}	15.92×10^{4}
12	Simulated Tubing-to-Fitting	Dissimilar	70/30 CuNi	0.007 O.D. 0.002 Wall Tubing	316 SS	0.005	BAg-1	Powder(c)	0.87	0.89	6	5.1	0.17	0.140×10^{3}	2.73×10^{4}

(a) For tee points: side No. 1 was butting member; side No. 2 was crossbar member.
(b) See Table 6b for filler metal details.
(c) With flux.
(d) No flux.
(e) Mixed with low-ash-content binder.
(f) Protective argon atmosphere used for all tests.
(g) Nd:YAG pulsed laser, wavelength = 106 μm; lens focal length = 100 mm; operated at TEM_{01} (transverse electromagnetic) mode.

TABLE 6b. Brazing Filler Metals

AWS Classification	Brazing Temperature, F (C)	Form Used	Chemical Composition, percent																Total Other Elements
			Ag	Cu	Zn	Cd	Ni	Sn	P	Cr	B	Si	Fe	C	Pb	Al	Au	Mn	
BAg-1	1145-1400) (619-760)	Powder	44-46	14-16	14-18	23-25	–	–	–	–	–	–	–	–	–	–	–	–	0.15
BAg-6	1425-1600 (774-871)	Powder	49-51	33-35	14-18	–	–	–	–	–	–	–	–	–	–	–	–	–	0.15
BAg-8	1435-1650 (780-899)	Powder	71-73	Bal.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.15
BAg-18	1325-1550 (719-843)	Powder	59-61	Bal.	–	–	–	9.5-10.5	0.025	–	–	–	–	–	–	–	–	–	0.15
BNi-2	1850-2150 (1010-1177)	Powder	–	–	–	–	Bal.	–	–	6.0-8.0	2.75-3.5	4.0-5.0	2.0-4.0	0.15	–	–	–	–	0.50
BCu-1	2000-2100 (1093-1149)	Foil	–	99.90 Min.	–	–	–	–	0.075	–	–	–	–	–	0.02	0.01	–	–	0.10
BAu-4	1740-1840 (949-1004)	Powder	–	–	–	–	Bal.	–	–	–	–	–	–	–	–	–	81.5	–	0.15
BA1Si-2	1100-1150 (593-621)	Foil	–	0.25	0.20	–	–	–	–	–	–	6.8-8.2	0.8	–	–	Bal.	–	0.10	0.15

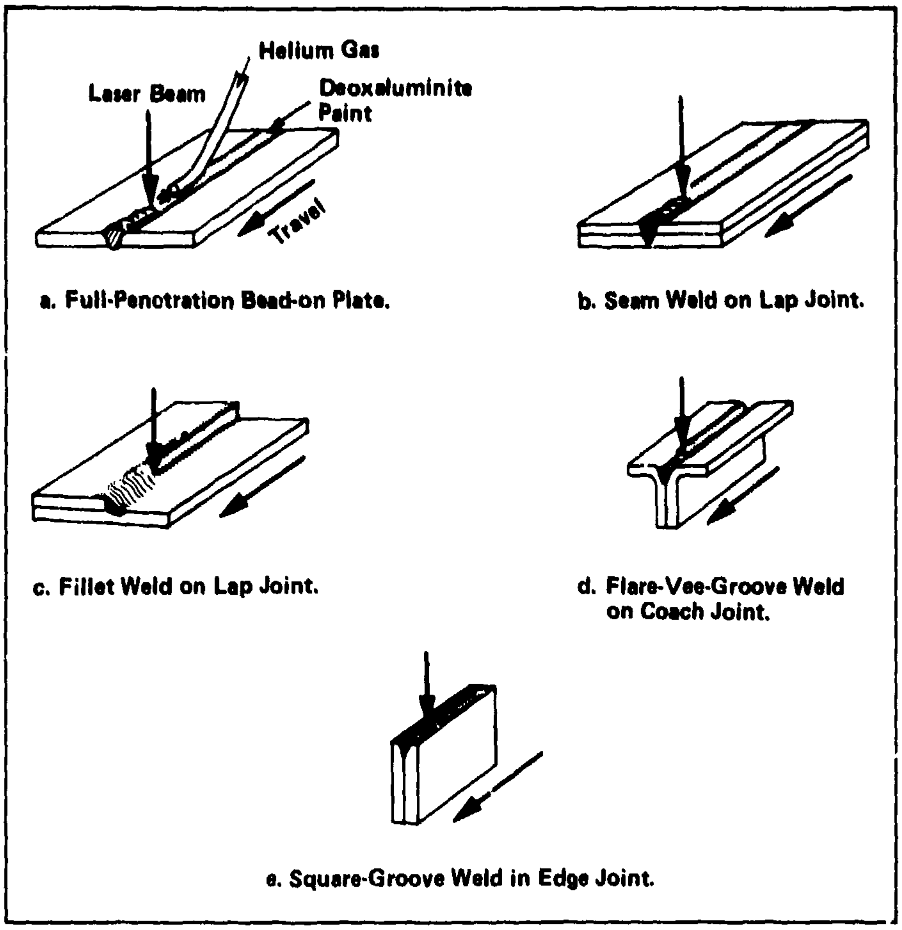


FIGURE 16. Types of Joints Made With CO_2 Laser in Deoxaluminite-Painted Rimmed Steel With Helium Shielding(37)

The welding performance of a 2000-watt continuous-wave CO_2 laser has been substantially improved by augmenting the input power of the laser beam with the energy provided by a gas tungsten arc.[40] In Figure 18, the gas tungsten-arc impinges on the underside of the workpiece and can also impinge on the topside of the workpiece in close proximity to the laser beam. When a 25-ampere gas tungsten arc located on the topside of the workpiece was used to augment the input power of the laser beam, it was possible to weld 0.032-inch-thick titanium sheet at about 1900 ipm.

Resistance Welding

While there are many variations of resistance welding (spot, seam, projection, flash, upset, and percussion), they are all based on the common principle that fusion at the faying or abutting surfaces of the joint members occurs as a result of the heat generated by the resistance of the workpieces to the passage of an electric current. These processes are classified according to the precise manner in which the heat required for fusion is generated as well as the type of joint that can be produced with each process. Since the principles of resistance welding are well known and application data are plentiful and readily available in

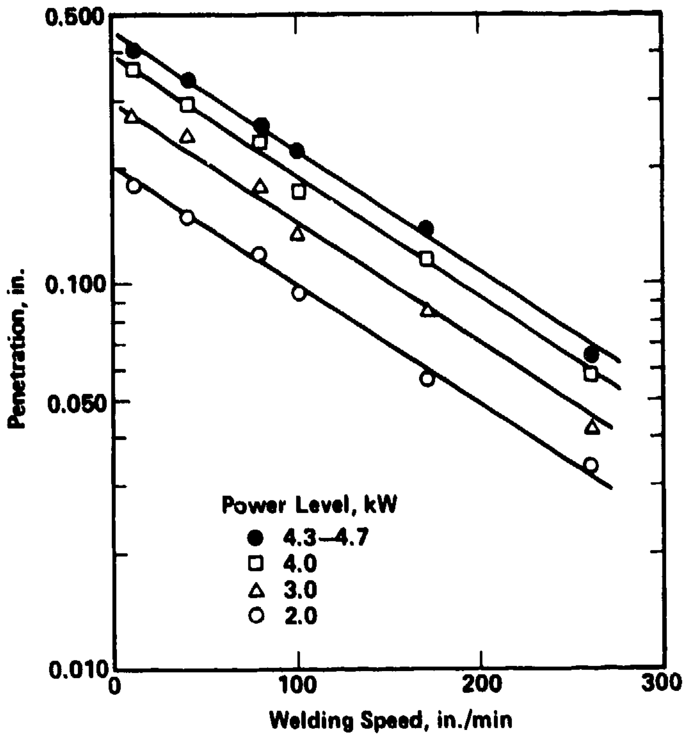


FIGURE 17. Weld Bead Penetration in Rimmed Steel as a Function of Welding Speed at Different Laser Power Levels(37)

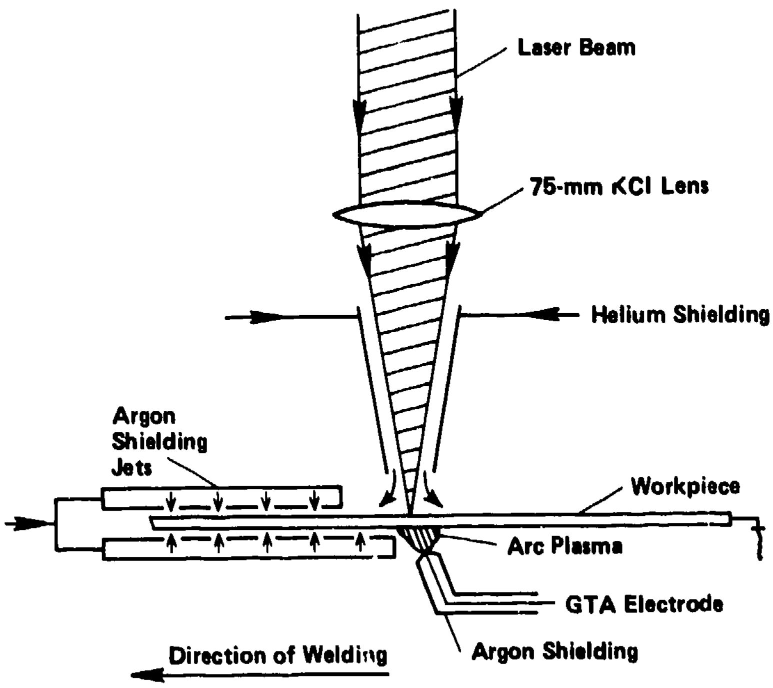


FIGURE 18. Augmented Laser Welding System(40)

sources such as the Welding Handbook, there is no need to discuss process details in this report. Instead, selected advances will be addressed in the following sections.

Spot Welding. Much of the recent activity in this area has been concerned with the development of procedures for the resistance spot welding of the high-strength sheet steels used by the automotive industry in current production. These steels (low alloy, high strength, dual-phase, stress-relievd annealed, rephosphorized, and nitrogenized) have been developed to reduce vehicle weight by replacing heavier-gage plain carbon sheet steels and thus improve fuel economy. All of these steels are weldable; however, their weldability varies in accordance with the manner in which the attributes of high-strength, good formability, and moderate cost are achieved. The procedures used to spot weld plain carbon steel can also be used to weld some of these steels; however, other steels require procedures that are modified to accommodate the difference in strength levels, the effect of composition, and the influence of rolling practices and other processing techniques. As a result, the producers and users of these new steels have combined efforts to develop optimum spot welding procedures.

For example, the spot weldability of rephosphorized and stress-relieved annealed sheet steels was recently examined.[41] Several mill-produced steels in both grades were included to evaluate materials with different chemistries and a wide range of strengths. The welding conditions were similar to those used in high-volume, high-speed production operations. In this instance, the results of metallographic evaluations, mechanical property tests, and quality control determinations indicated that spot welds with adequate size, strength, and toughness could be produced in both grades of steel under conditions similar to those used for spot welding plain carbon steelsheets. Because of the higher base metal strengths, spot welds in these steels had higher tensile-shear strengths than welds in plain carbon steels. In another investigation, the spot welding characteristics of a high-strength, low-alloy steel with a minimum yield strength of 80,000 psi were examined and compared with those of plain carbon sheet.[42] It was found that this steel could be readily welded with the same electrode, electrode force, and welding time used for welding carbon steel. However, because of its higher carbon and alloy content, the resistivity of this steel was higher than that of plain carbon steel and the welding current had to be accordingly reduced.

Significant progress has been made in the development of equipment to monitor and control the spot welding parameters, and programming devices are being used extensively in the automotive industry to establish, store, and use complex welding schedules in conjunction with spot welding robots. Adaptive or feedback control equipment is also available for quality control purposes. In some instances, current or voltage provides the reference signal while other variables are monitored in other cases. For example, equipment capable of detecting expulsion by acoustic emission techniques is being currently marketed.[43] The design of this equipment is based on the principle that stress waves are emitted by solid materials when they are stimulated by mechanical or thermal means, e.g., as they are during spot welding. These waves can be detected by a transducer and processed electronically for process control. For example, in resistance spot welding, expulsion occurs when an oversize nugget forms and it is generally indicative of overwelding. The acoustic emission signals associated with expulsion can be readily detected and the welding process can be terminated immediately with no loss in nugget shear strength. Other claimed advantages include increased electrode life, reduced energy consumption, and reduced flashing. The magnitude of dynamic resistance at various stages in the formation of a spot weld has been also investigated as a means to control quality during welding.[44] This parameter is a measure of the changing resistance between the spot welding electrodes during the welding cycle. The measurement is derived with equipment designed to divide the instantaneous voltage by the instantaneous current. The equipment then processes the data electronically, and records dynamic resistance, power, and other parameters; a block diagram of this equipment is shown in Figure 19. The events that occur during the production of a spot weld (surface breakdown, asperity collapse, workpiece heating, molten nugget formation, nugget growth, and mechanical collapse) were related to the dynamic resistance as shown in Figure 20. Dynamic resistance data were also related to lobe curves that define the parameter limits within which acceptable spot welds can be produced. Dynamic resistance monitoring appears to be a promising in-process quality control method.

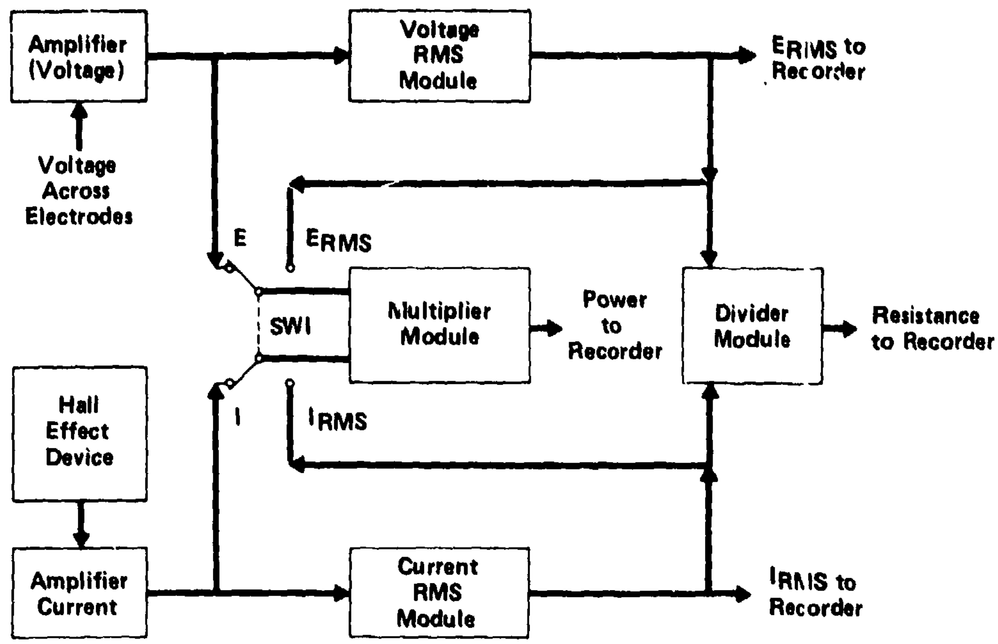


FIGURE 19. Block Diagram of Circuit Elements Used to Measure Spot Welding Dynamic Resistance Parameters(44)

Flash Welding. The capabilities of resistance flash welding have been significantly expanded by the development of equipment to produce girth welds in large-diameter line pipe.(45) This equipment has been designed and constructed in the Soviet Union for pipeline construction in arctic regions and is being used under field conditions there; it is also being marketed in the West. An internal machine is available for welding 48-inch-diameter and 56-inch-diameter pipe and similar machines for samller diameter pipe are also being developed.

In flash welding, fusion is produced over the entire area of two abutting surfaces. The heat required for fusion is generated by the resistance of minute contact points to the passage of current. Pressure must be provided to expel the molten weld metal and upset the joint. The cross-sectional area that can be welded is largely dependent on the electrical rating of the transformer and the capacity of the hydraulic system. Since large surface areas are often difficult to heat uniformly, most applications are confined to the welding of workpieces with areas of 15 square inches or less. In the pipe welding machine, nonuniform heating was

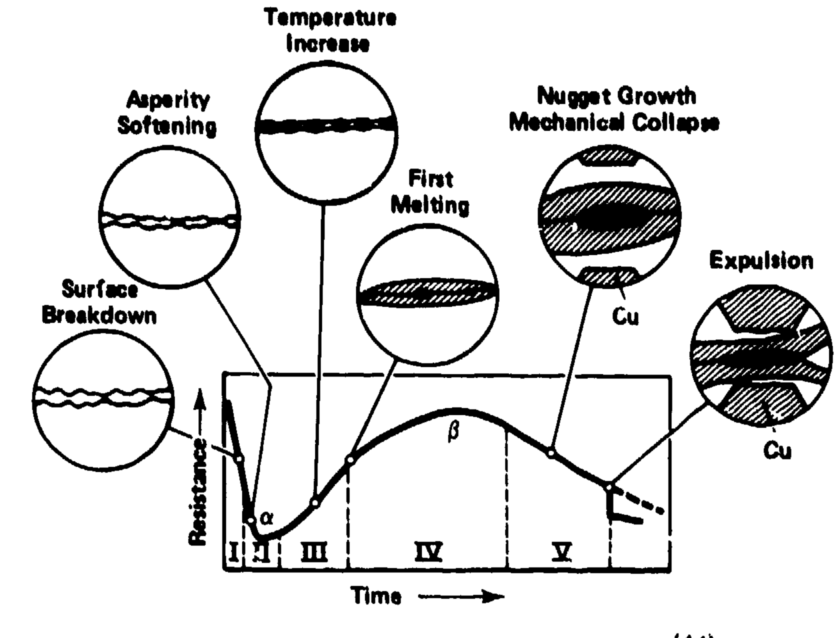


FIGURE 20. Theoretical Dynamic Resistance Curve(44)

essentially eliminated by impulse flashing produced by mechanically vibrating the pipe sections as they were brought into contact. An improved electrical circuit design was used to decrease transformer size by reducing the circuit impedance. This welding equipment is being used currently in pipeline construction and the rate of production is 6 to 8 girth joints per hour in 56-inch-diameter pipe with a wall thickness of about 7/8 inch. The pipe is usually double or triple jointed in a pipeyard to reduce field welding operations. Welding productivity has been improved appreciably because there are only 10 to 12 members in the line crew as opposed to about 50 members in a conventional welding crew.

Another process that may be suitable for welding workpieces with large surface areas is based on the use of a pulsed homopolar generator.[46] Homopolar generators are low-voltage, high-current devices that date back many years. However, pulsed generators of this type are a spinoff of research to develop large, pulsed power supplies for thermonuclear fusion experiments. A 5-megajoule machine has been used to experimentally flash weld 2- and 4-inch-diameter boiler pipe and 4-inch-diameter stainless steel pipe. Welding times ranged from 1/2 to 1 second at a power of about 250 kilowatts. The process capabilities could be extended appreciably with the development of larger machines.

Solid-State Welding Processes

Explosive Welding

Explosive welding is based on the principle that solid-state welding between the overlapped surfaces of two workpieces can be achieved by using the energy produced by a detonating explosive to accelerate the joint components across a properly configured and dimensioned gap. Under the proper conditions, a phenomenon known as jetting occurs.

Jetting is a necessary prerequisite of metallurgical bonding, because the jet cleans the surfaces of the colliding joint members and allows welding to occur in a fraction of a second at the moving collision point. This is an ambient temperature welding process. While gross heating of the workpieces does not occur, the faying surfaces are heated to some extent by the energy associated with the collision. Welding is accomplished by plastic flow of the metal on these surfaces. The joint interface can be flat or wavy; however, a wavy interface is most indicative of a well-bonded joint with optimum mechanical properties. The formation of a joint with a wavy interface is shown in Figure 21. Some of the interrelated variables that must be controlled during welding are the collision velocity, collision angle, and plate velocity.

This process can be used to weld a wide variety of similar and dissimilar metals, some of which cannot be joined by other means. Some dissimilar metal combinations that have been successfully welded appear in Figure 22.[23] Generally, any metal with sufficient strength and ductility to withstand the required deformation at the velocities associated with this process can be welded. Welding can often be done without affecting the prior metallurgical history of the workpiece. However, in general, strength and hardness increase and ductility decreases in the near vicinity of the joint.

While explosives and explosive devices are inherently dangerous, safe methods to handle them are available. Explosive materials should be handled and used only by experienced personnel. Handling and safety procedures must comply with all applicable regulations.

Several applications of explosive welding are discussed in the following sections and specific advances in recent years are also cited.

Cladding. Explosive welding has been used most extensively on a commercial basis for the cladding of flat plate with metals that provide resistance to corrosion, oxidation, wear, and other forms of attack. The importance of cladding applications will increase significantly in future years with the continuing need to conserve metals that are in short supply. Depending on customer requirements, the base or backer plate can be clad on one or both sides. The capabilities of this process have been extended in recent years, and plates with areas in excess of 300 square feet can be routinely clad. In fact, cladding capabilities are largely limited by the dimensions of commercially available plate. Clad plate is often used in the as-welded condition to fabricate heat exchanger tubesheets and vessels of various types for the petrochemical and related industries. Such plate is also sectioned for the production of transition sections. In many instances, clad plate is conversion rolled to the thicknesses required for composite coinage and other products. Typical shear strengths of joints in some of the most commonly clad materials are shown in Table 7.[47]

Cladding operations are also conducted to increase the service life of nozzles, cylindrical structures, conical members, and other parts with relatively simple contours.

Transition Sections. The fabrication of transition sections constitutes another major application of explosive welding. Such sections are used to facilitate the joining of metals that are difficult or impossible to join by other welding methods because of their metallurgical incompatibility (e.g., the joining of aluminum to steel, titanium to steel, aluminum to copper, and many other dissimilar metal combinations). Transition sections are most commonly applied in the shipbuilding industry where their use permits metal-to-metal joining of the

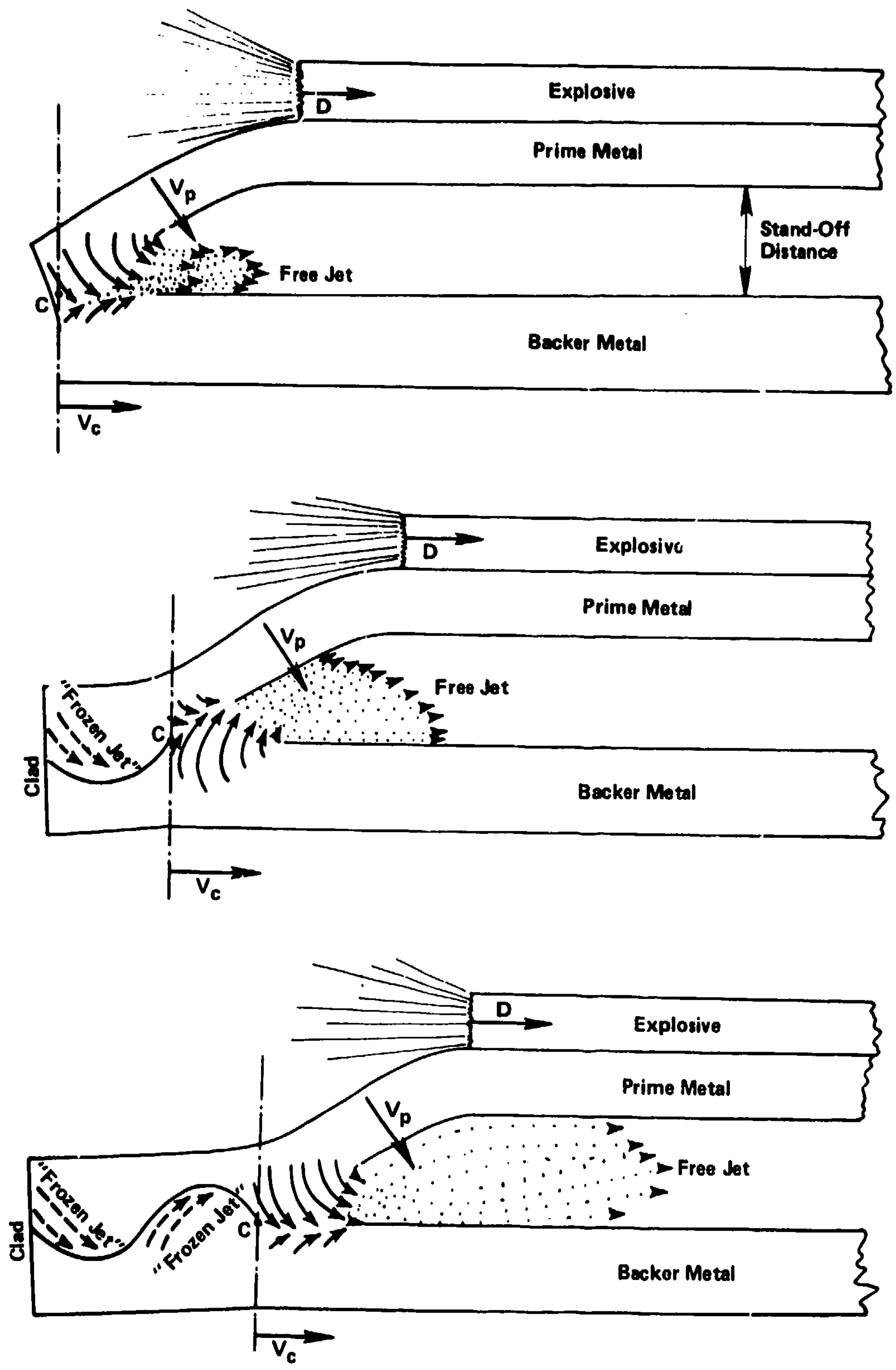


FIGURE 21. Stages in Formation of Explosive Welded Joint(120)

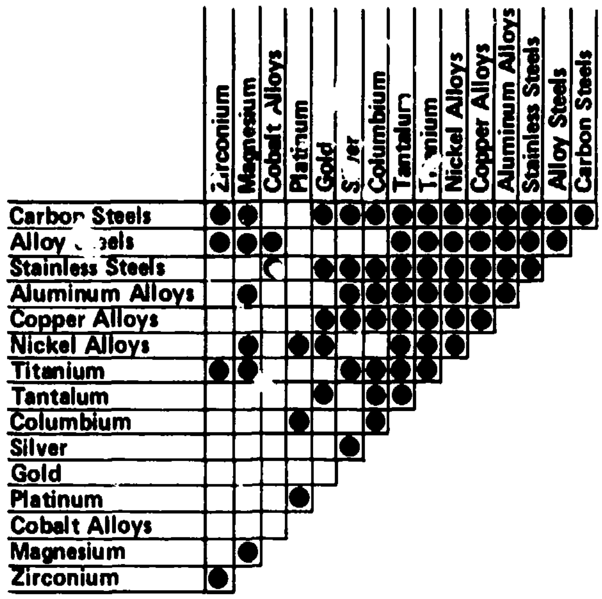


FIGURE 22. Some Similar and Dissimilar Metal Combinations That Have Been Explosively Welded[23]

TABLE 7. Typical Shear Strengths of Joints in Explosively Clad Plate[47]

Cladding Metal[a]	As-Clad Shear Strength, psi
Stainless steels	66,700
Nickel and nickel alloys	60,500
Copper	22,000
Cupro-nickel	36,400
Titanium[b]	39,000
Zirconium	49,000
Aluminum	13,900

(a) Carbon steel base plate.
(b) Stress-relief annealed.

aluminum superstructure to the steel decking. In this instance, the use of an aluminum-steel transition section produces joints that are strong and maintenance-free. It also eliminates a source of crevice corrosion that is common to bolted or riveted construction. Simple transition sections of this nature are merely cut from flat clad plate. Similar sections from aluminum-clad steel and aluminum-clad copper plates are used extensively in various electrical applications.

Short tubular transition sections can be trepanned from thick flat clad plate. Longer sections can be made with lengths of tubing that are telescoped to produce a relatively long lap-joint configuration. Depending on the location of the explosive charge, support tooling will be required on the inside or outside of the joint assembly to maintain the dimensional stability of the parts during the welding operation. Tubular transition sections can be made in a variety of sizes but most are 12 inches in diameter or less. Aluminum-stainless steel transition sections are used for cryogenic applications, such as in the construction of vessels for transporting liquefied natural gases. Aluminum-steel sections are used to connect aluminum components to steel piping systems. Other common metal combinations used in tubular transition sections include titanium to steel, titanium to stainless steel, zirconium to stainless steel, zirconium to nickel, aluminum to copper, etc.[48–50]

Pipe Welding. Explosive welding has also been used to make girth joints between sections of pipe with diameters of 30 inches or more.[51] The pipe can be joined end-to-end with a collar or a telescoping joint configuration. Welding can be done using an explosive charge located on the inside or outside of the pipe; depending on the charge location, internal or external tooling is used to maintain the dimensional stability of the joint members during welding. This process has also been investigated as a means to weld line pipe underwater with appropriate changes in the technology to exclude water from the joint area.[52,53] The welding of large-diameter pipe has also been accomplished without the need for internal or external tooling by the use of specially developed explosive charges and techniques.

Tube-to-Tubesheet Welding and Tube Plugging. Explosive welding procedures have been developed and used commercially as a cost-effective method to fabricate tube-to-tubesheet joints in large heat exchangers.[54,55] As indicated in Figure 23, the holes in the tubesheet are counterbored to permit an angular detonation that results in a joint with optimum length. Following insertion of the tubes in the tubesheet, small specially designed explosive charges are placed inside the tubes and detonated. Several tube-to-tubesheet joints can be made simultaneously, however, to prevent distortion of adjacent holes in the tubesheet, it may be necessary to insert supporting plugs in them. Both similar and dissimilar metal tube-to-tubesheet joints can be produced in this manner. Variations of these procedures have also been used to plug leaking tubes in heat exchangers, thus permitting continued use of the equipment with minimum downtime.

Other Applications. The capabilities of explosive welding have been extended to include (1) the cladding of gas turbine components with metals that are resistant to oxidation, corrosion, and wear, (2) the repair of worn bearing journals on helicopter shafts, and (3) the fabrication of channeled components with simple and complex contours.[56] This process has been also used to fabricate multilayer laminated panels[57] and join multifilament Nb-Ti/Cu superconductors for fusion magnet applications.[58] For example, explosively laminated panels with alternating layers of a strong, tough material (Ti-6Al-4V) and a soft, ductile material (2024-T3 Al) are particularly interesting from the viewpoint of designing damage-tolerant structures for aircraft, because the resistance of these panels to fatigue, fracture, and crack propagation is superior to that of either component metal.[59] Laminated panels comprised of alternating layers of steel and copper have also been fabricated in this manner.

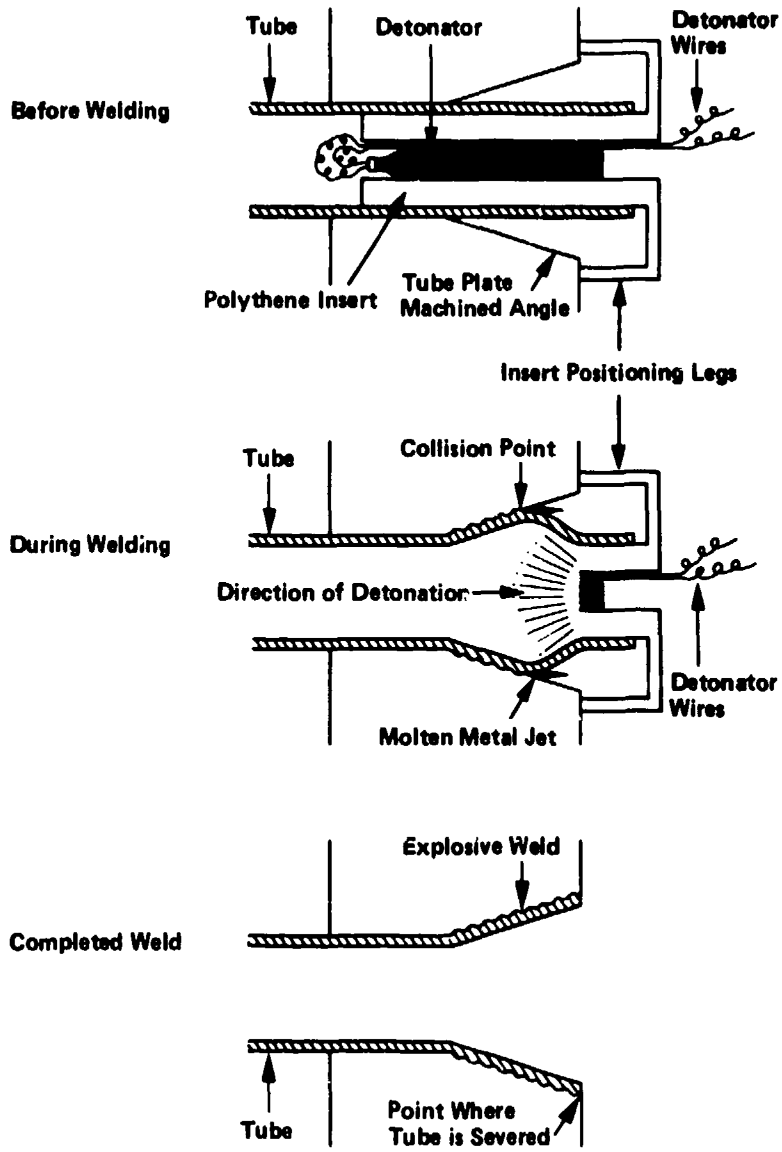


FIGURE 23. Explosive Welding of Tube-To-Tubesheet Joints(54)

Friction Welding

In this solid-state bonding process, the heat required for welding results from the frictional heating produced by the rotation of the joint members against one another under pressure. As indicated by the following, there are two variations of this process:

- In conventional friction welding, one workpiece is attached to the motor drive and rotated at a constant speed. Pressure is then applied to produce frictional heating of the faying surfaces of the rotating and stationary workpieces. At the end of the heating cycle, the motor drive is disengaged, the rotating workpiece is braked to a standstill, and pressure is increased to upset the joint.

- Inertia welding is the version in which one workpiece is attached to a flywheel. The flywheel is accelerated to a selected speed, storing energy as it rotates. Then the flywheel drive is disengaged and the workpieces are brought into contact under pressure. Heating occurs as the faying surfaces of the workpieces rub together. Heating continues as the flywheel energy is dissipated and the speed of the flywheel decreases. As the hot weld zone upsets under pressure, the torque peaks just before rotation ceases. An additional upsetting force may be applied as the flywheel torque reaches a maximum.

Additional information on these process variations is available in the literature.[23]

Both variations of friction welding are proven production processes. They can be used to join a wide variety of similar and dissimilar metals, including some dissimilar metal combinations that are difficult or impossible to join by other means (Figure 24). However, the

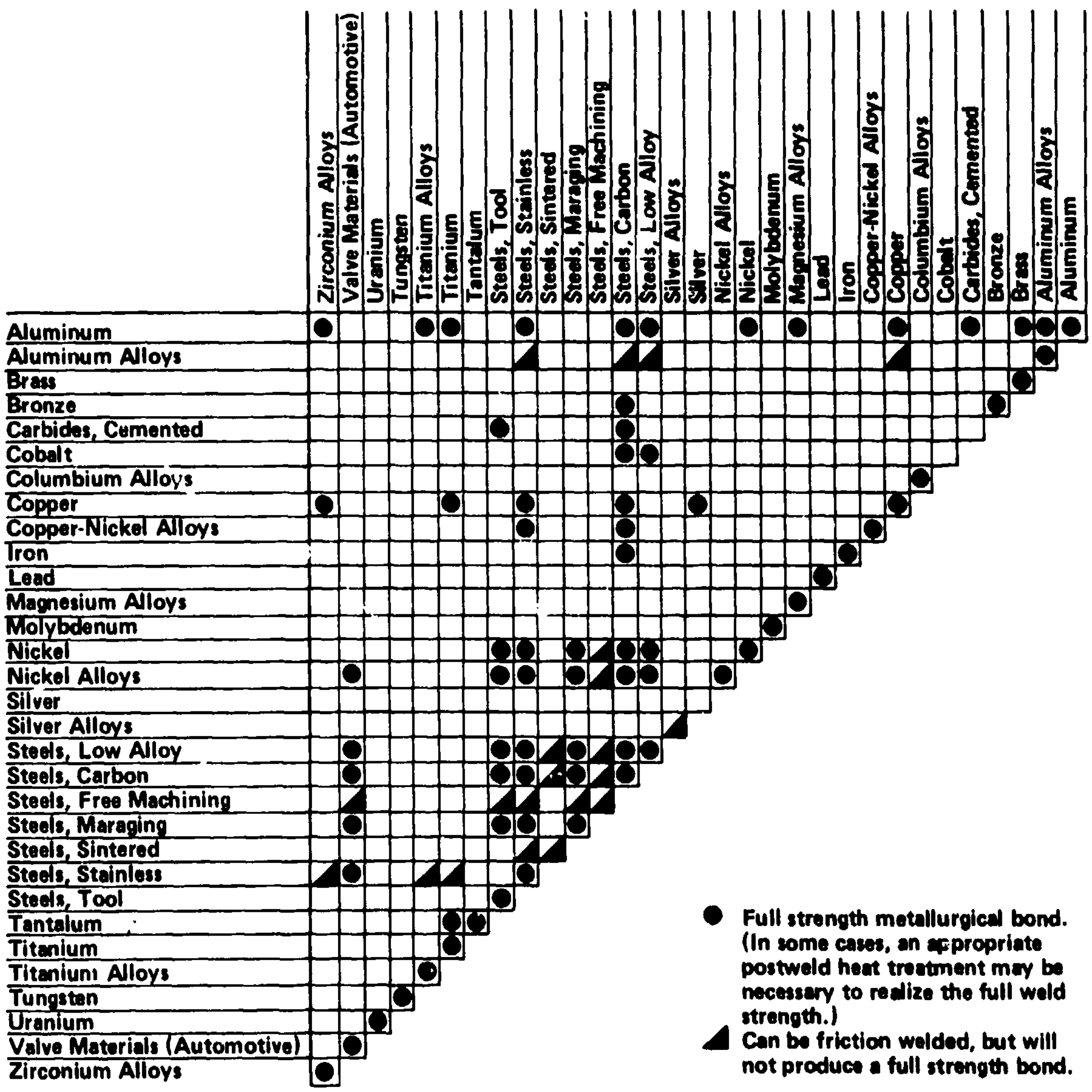


FIGURE 24. Friction Weldability of Similar and Dissimilar Metals[23]

weldability of some combinations is dependent on the metallurgical compatibility of the respective base metals. Friction welding produces savings in materials, time, and energy, because filler metal is not required and joining can be accomplished in a matter of seconds. The cleanliness of the workpiece surfaces rarely presents problems and these processes lend themselves to a high degree of automation. Friction welding does have its drawbacks, of course. One joint member must be round or nearly so, the joint surfaces must be perpendicular to the axis of rotation, upset removal may be necessary, and designs to produce uniform heating of the joint may be critical. However, the friction welding processes have been widely accepted by industry for many critical welding applications. For example, one aircraft engine manufacturer has recently installed a large inertia welding unit that can be used to weld tubular joint members with diameters as large as 36 inches. It will also be used to weld gas turbine components.[60]

Conventional friction welding is frequently used to attach tool joints to drill pipe.[61] The pin and box joints are made from a 4000-series medium-carbon steel and the diameters of such joints range from about 3-1/4 to 7 inches, depending on the diameter of the pipe to which they must be attached. Steel drill pipe in diameters ranging from 2-7/8 to 5 inches is available in several grades with minimum yield strengths that vary from 55,000 to 135,000 psi. In this critical joining application, it is necessary to control and monitor rotational speed, braking time, and the amount of upset. Heat treatment is generally required to achieve the required joint properties.

Inertia and electron-beam welding procedures have been combined to fabricate a four-part power shaft for a gas turbine engine.[62] The power shaft consisted of a D-979 nickel alloy disc and aft shaft, a 17-22AS low-alloy steel front shaft, and an AISI 9310 front stub shaft. The tubular disc-to-aft shaft and aft-to-front shaft joints were made by inertia welding with conditions based on the cross-sectional area of the respective joints. The front stub shaft was attached to the inertia-welded assembly by electron-beam welding. Careful fixturing was needed to maintain the dimensional stability of the power shaft during welding.

Applications for friction and inertia welding abound in the automotive, aircraft, hydraulics, oil and gas, and many other industries. Typical examples are cited in a recent paper by Ellis.[63]

Diffusion Welding and Diffusion Brazing

As their names imply, diffusion welding and brazing are processes that depend on diffusion principles for joining. While there are many similarities between these processes, there are important differences that have a bearing on the precise manner in which joining is accomplished. The distinguishing features of each process are discussed in the following sections:

- Diffusion welding is the oldest of these two processes. It is a process in which the formation of the joint is dependent on solid-state diffusion. Joining at the faying surfaces of the workpieces is achieved by the application of pressure at elevated temperatures for a selected period of time. Melting along the joint interface does not occur during the welding cycle. Depending on the base metal characteristics, a diffusion aid in the form of a foil made from another metal may or may not be needed to facilitate the diffusion process or improve the contact between the joint surfaces. Usually, the interface metal is diffused into the base metal by a suitable heat treatment.

- Diffusion brazing is a more recent development that depends on the presence of a filler metal or an in situ liquid metal phase to accomplish joining. The filler metal may be preplaced between the joint surfaces or it may be distributed into the joint by capillary attraction; it may also form between the joint surfaces during the bonding cycle. Pressure may or may not be needed for joining. Since the filler metal is diffused into the base metal, a distinct layer of filler metal does not exist after completion of the diffusion brazing cycle.

These two processes can be used to produce joints between a wide variety of base metals. They are particularly useful in the production of joints between dissimilar metals that cannot be readily joined by other means because the respective metals differ widely in their physical and metallurgical properties. Under the proper conditions, welds with properties and microstructures that closely resemble those of the base metals can be produced. Despite their obvious attributes, these processes are usually used for critical assembly operations involving the joining of aluminum, titanium, and nickel alloys for aircraft, space, and missile applications, because production rates are relatively low, equipment and fixturing costs are high, and parts preparation and fitup are critical.

Since the capabilities of conventional diffusion welding and brazing were covered in considerable detail in an earlier MCIC publication "Advances in Joining Technology-The 1960's and Beyond", there is little need to review this area again. Instead, a few articles reflecting recent accomplishments are cited in the reference section of this report.[64-69]

One recent process variation, superplastic forming diffusion bonding (SPF/DB), merits discussion because it provides an opportunity to increase the productivity of diffusion welding operations and decrease the weight of fabricated components. By taking advantage of the superplastic properties of certain metals and alloys, it permits the forming and welding of complex components for aircraft and missile applications. For example, Ti-6Al-4V, the alloy used most extensively for aerospace applications, can be superplastically formed (with elongations up to 1000 percent) and diffusion welded at temperatures that are somewhat below the beta transus of this alloy. Forming and welding operations accomplished at low applied pressures can be combined for maximum cost-effectiveness, if the parts configuration is suitable for processing in this manner. The operations can be conducted separately also.[70-71]

Several titanium alloy sheet metal structures that have been fabricated in this manner are shown in Figure 25a and the details of processing a simple structure are shown in Figure 25b. In the instance where superplastic forming and diffusion welding were combined, the cleaned titanium sheets were placed in a closed die set after the areas in which bonding was not desired were coated with a stop-off material. Diffusion welding was done at 1600-1750 F under an applied gas pressure of 200 to 300 psi. After welding, gas pressure was used to superplastically expand the unbonded sections of the structure into the female die. Various stiffened structures for the B-1 bomber were produced in this manner. Additional studies to produce components with cylindrical as well as planar contours are under way. Recent efforts by government contractors to exploit this process are cited among the references.[72-74]

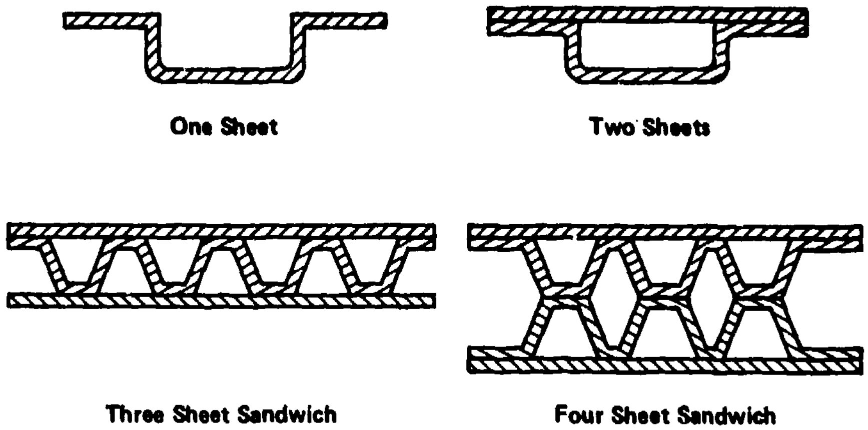


FIGURE 25a. Titanium Alloy Sheet Metal Configurations Produced by Superplastic Forming/Diffusion Bonding Process[69]

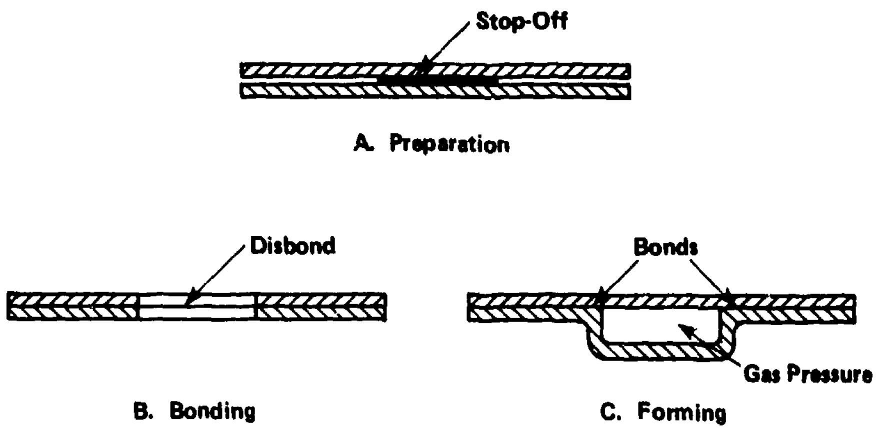


FIGURE 25b. Schematic of Superplastic Forming/Diffusion Bonding Processing[71]

Other Processes

Brazing

Brazing includes a group of processes in which joining is accomplished by heating closely fitting workpieces to a suitable temperature and causing a filler metal to flow into the joint by capillary attraction. By definition, the melting temperature of the filler metal must be above 840 F and it must be below the melting temperature of the base metals. While capillary attraction to distribute the filler metal into the joint is a general process requirement, brazing can be sometimes accomplished in its absence by proper preplacement of the filler metal in the joint. Detailed information on brazing (process capabilities and limitations, heating methods, filler metals, fluxes and atmospheres, joint characteristics, etc.) is readily available in the Welding Handbook and other sources.

Advances in brazing have kept pace with those in other areas of metals joining. Much of the research concerned with the development and evaluation of new filler metals has been spurred by technical considerations. However, economic pressures have prompted efforts to develop low-gold and gold-free filler metals for application where alloys with large contents of gold are commonly used. Also, technical advances in other areas have been used to increase brazing productivity. For example, certain alloys have been produced as foils, a form in which they were previously unavailable. Selected developments are discussed in the following sections.

Metallic Foils. Until recently, most nickel-base filler metals were not available in the form of sheet or foil because of the inability to roll these low-ductility nickel alloys. As a result, productivity has lagged in some instances because of the increased joint assembly time. Boron is widely used as a melting-point depressant in many conventional nickel-base filler metals in amounts ranging from 2 to 4 percent. At these boron levels, the nickel-base filler metals have little or no ductility and cannot be fabricated into sheet or wire. As a consequence, these alloys are available only as powders, pastes, transfer tapes, and plastic-bonded powders in sheet or wire form. Phosphorus is also used as a melting-point depressant in other nickel-base alloys, and these alloys are equally difficult to fabricate. While the nickel-base filler metals in powder and other available forms are used extensively for high-temperature brazing applications, there are many instances where foils could be used advantageously. For example, difficulties may be experienced in applying powders to the joint area in consistent amounts and in maintaining dimensional control of the brazing clearances with plastic-bonded sheet materials. Also, when plastic-bonded powders are used, defects in the brazed joints may occur because of volatilization of the binder constituents during brazing or because of the presence of binder residues. The following two methods have been used to produce ductile nickel-base filler metal foils:

- In one instance, a master alloy containing all of the filler metal constituents except boron was produced using standard melting practices. This alloy was quite ductile and could be reduced to foil by conventional rolling practices. Then, boron was diffused into the foil surfaces in amounts sufficient to achieve a level of about 3 weight percent. The borided-foil retains its ductility because of the ductile boron-free core, and it can be used as-fabricated or it can be stamped into preforms of various sizes and shapes. During brazing, the entire foil melts to form a homogeneous liquid. Wire could be produced in a similar manner by drawing the boron-free master alloy into wire and diffusing boron into its surfaces. This production technique is applicable to all of the nickel-base filler metals that contain boron as a melting-point depressant.[75]

- New technology has been used to supercool a molten filler metal at rates in excess of 100,000 C/sec and produce a foil with the same random arrangement of atoms that exists in the molten alloy.[76] These amorphous rather than crystalline foils are extremely ductile and can be bent through an angle of 180 degrees without fracturing. The metallic glass foils can be used in the as-processed condition or they can be stamped into preforms. Several nickel-base filler metals containing boron or phosphorus as melting-point depressants are available as metallic glass foils in widths up to 2 inches and in thicknesses ranging from 0.0005 to 0.002 inch. Small-diameter wire can also be produced by fast liquid-metal quenching methods.

These 100 percent dense borided and metal glass foils can be used for brazing in the same manner as foils produced from filler metal based on silver, gold, copper, and other ductile metals. They are particularly useful in applications where joints with large surface areas must be brazed or where the amount of alloy applied to the joint must be controlled within close limits. The strength characteristics of joints brazed with these metal-glass foils are similar to those of joints brazed with an alloy powder having the same composition (Table 8) and the joint microstructures are similar also.

TABLE 8. Mechanical Properties of Joints Brazed with the Same Filler Metal[a] in Various Forms[76]

Overlap	Metallic Glass Foil	Borided Foil	Powder Paste
	Shear Strength, psi		
1t	31,900	--	47,300
2t	21,500	--	19,500
3t	18,500	18,600	15,900
	Tensile Strength, psi		
1t	34,700	--	50,700
2t	58,900	--	45,100
3t	56,000	50,800	56,700

(a) BNi-2 Filler Metal (Ni-7.0Cr-3.1B-4.5Si-3.0Fe).

Clearances: 0.015 inch for metallic glass and powder paste;
0.0033 inch for borided foils.

Low-Gold and Gold-Free Filler Metals. Au-18Ni and other high-gold filler metals are used widely in the aircraft industry to braze the component parts of many assemblies that are exposed to the critical environment associated with the hot sections of gas turbine engines. These filler metals wet most structural alloys used in engine fabrication and possess excellent flow characteristics. Joints brazed with these alloys are strong, ductile, and oxidation resistant, in addition to being resistant to attack by the corrosive gases that are present during engine operations. In contrast to the nickel-base brazing alloys, filler metals with large contents of gold do not react severely with most engine materials during the brazing cycle. As a result, there is a decreased tendency to form joint microstructures with limited ductility, and these filler metals can be used to braze thin as well as thick joint members. Similar and dissimilar metal joints can be produced readily in a vacuum or in an inert or reducing atmosphere. The high-gold filler metals are available in wire, sheet, powder, etc. forms that permit efficient assembly of the joint components.

Despite their cost, the use of high-gold filler metals in production brazing operations was commonplace before the precipitous increase in the price of gold. This is no longer the case. These filler metals are very expensive, and it is difficult to project their costs in the future because of daily fluctuations in the price of gold. In view of their many advantages, the high-gold filler metals are difficult to replace, but efforts to do so have been under way for several years. While the nickel-base filler metals appear to be logical substitutes for those with large gold contents, they have disadvantages that detract from their potential usefulness (excessive interfacial reactions with many base metals, the formation of microstructures with limited ductility, etc.). Minor changes in the composition of selected nickel-base filler metals have resulted in improved brazing performance, but problems still remain. The results of efforts to develop alternative brazing alloys are discussed:

- In some instances, efforts have been made to retain the attributes of the high-gold filler metals by decreasing the gold content through the use of less expensive alloying additions. For example, recent endeavors have resulted in the development of the following filler metals for rocket nozzle brazing applications: Cu-35Au-10Pd-14.5Ni-9.5Mn-0.1La and Cu-38Au-2.5Pd-4.3Ni-8Mn-0.1La.(77) Since the brazing ranges for these alloys are 1900 to 1925 F and 1775 to 1850 F, respectively, they can be used for step brazing as well as for conventional brazing operations. Both alloys are ductile and can be produced in the form of foil, wire, powder, etc. Brazing can be done in a vacuum or in a controlled atmosphere. Reportedly, these low-gold alloys have excellent wetting and flow characteristics, and the brazed joints are resistant to oxidation and salt-spray corrosion. The following nickel-base alloys with low contents of gold have also been developed: Ni-20.5Au-3.4Si-5.3Cr-2.3B-2.3Fe and Ni-41.0Au-1.75Si-1.0B-0.5Fe.
- Several gold-free filler metals are available for use as substitutes for Au-18Ni and other high-gold alloys. For example, Cu-31.5Mn-10Co has been used on a limited basis for aircraft engine brazing applications with considerable success.(78) Other copper-manganese and nickel-manganese alloys are being considered for similar applications despite the relatively poor flow characteristics of manganese-containing alloys. Two recently developed nickel-palladium filler metals (Ni-36.0Pd-11.0Cr-2.2Si-2.1B and Ni-25.0Pd-14.5U-6.0Cr-1.5B) are promising replacements for high-gold alloys.(79,80) In this instance, palladium is acceptable for alloying purposes despite its cost, because it is less expensive than gold. The wetting and flow characteristics of these alloys are excellent and they possess acceptable gap-filling capabilities. Brazing can be done in a vacuum or in a controlled gaseous atmosphere. Joint characteristics are similar to those obtained with representative high-gold alloys.

Other Developments. Improvements in nickel-base filler metals for specialized applications have also been made. For example, several filler metals with phosphorus as a melting-point depressant instead of boron have been developed for applications in the nuclear industry. Among them are the following: Ni-25Cr-10P, Ni-26.3Cr-5.1Si-3P, Ni-14.8Cr-8Si-3P-3Fe, and Ni-20.3Cr-11.5Si-0.5P.(81,82) While these alloys were developed for a specific purpose, they should be equally useful in general brazing applications where high-strength joints with good resistance to oxidation and corrosion are required.

Research efforts have also been directed toward the development of filler metals for brazing the reactive and refractory base metals. Typical of these efforts is one in which a series of experimental high-temperature filler metals for the leaktight sealing of structures made from molybdenum and tungsten were investigated.[83] The following filler metals were judged most suitable for this application: Ti-65V, V-50Mo, MoB-50MoC, and pure vanadium. However, to avoid the formation of Kirkendall voids, it was necessary to dilute the brazing alloy with the base metal by various techniques.

Spot Welding—Adhesive Bonding

"Weldbonding", a word coined to denote the combination of spot welding and adhesive bonding, was developed to combine the advantages of both processes in the fabrication of sheet metal structures. This process has been investigated as a means to improve the static and dynamic fatigue characteristics of aircraft structural members while minimizing production costs. Resistance spot welding is a well-developed production process designed for assembling sheet metal parts at low costs and high rates. However, in some instances, the full benefits of spot welding have not been realized, because individual spot welds act as stress risers and impair the fatigue properties of such structures. In contrast, adhesive-bonded structures have outstanding fatigue characteristics, since the uniform distribution of loads over the entire bonded area eliminates stress concentrations. However, such structures are often costly to assemble and fixture for bonding. As a result, there is a strong incentive to combine these processes.

Weldbonding can be accomplished in two ways, the most common of which involves the spot welding of sheet metal components whose surfaces have been coated with an appropriate adhesive. While this procedure is the more direct and produces the best results, extensive research has been conducted to develop cleaning methods that are equally effective in preparing the joint surfaces for spot welding and adhesive bonding. Weldbonding can also be accomplished by using capillary attraction to infiltrate a low-viscosity adhesive into a spotwelded assembly. Process benefits resulting from research conducted in the mid-1970s are indicated:[84]

- The fatigue performance of spot-welded and adhesive-bonded joints in aluminum sheet metal structures was better than that of spot-welded joints alone.
- Adhesive bonding costs were reduced because the spot welds held the structural members together while the adhesive cured.
- The joints were sealed as well as bonded during processing.

It was noted that compromises were necessary, because the surface preparation for optimum welding was not the same as that for optimum bonding.

The development of weldbonding as a viable production process has been accomplished by those concerned with the fabrication of sheet metal assemblies for aircraft and space applications, and work to extend process capabilities in this area continues to date.[85,86] As a result, the use of this process has been largely confined to the joining of aluminum structures with limited efforts being directed toward the weldbonding of titanium sheet materials also.

However, it would be advantageous if the method could be used to produce structures made from materials other than those used in the aircraft industry. For example, the ability to process steel sheet assemblies in this manner would provide the automotive industry with another weapon to combat rising production costs. Efforts in this area are discussed in the following section:

- Studies have been conducted to develop procedures for the combined spot welding and adhesive bonding of 0.050-inch-thick carbon steel sheet stock with adhesives of the following types: epoxy resin-based adhesives, nitrile-based adhesives, and cyanoacrylate-based adhesives.[87] Welding through all of these adhesives could be accomplished without difficulty using conditions similar to those for conventional spot welding, if welding was done immediately after the application of the adhesive. Although the tensile, shear, and impact strengths of the welds were not improved, the energy required to fracture the welds was increased markedly. Also, the buckling loads of similar lightweight profiles indicated the superiority of weldbonding over spot welding.

Health and Safety

Studies of the welding environment represent a significant development in the commitment of industry to provide working conditions that promote the health and safety of welders and those in similar occupations. The hazards associated with welding, cutting, and related operations have been a matter of concern for many years. The Occupational Safety and Health Act of 1970 added the force of law to these concerns and investigations of the conditions to which welders are exposed were accordingly accelerated. Domestic research efforts in this area have been paralleled by those in most industrialized countries and a large background of useful data has been accumulated as a result. The characteristics of the welding environment are discussed in this section, and some sources of information are referenced to provide guidance for those concerned with the safety and health aspects of welding.

The welding environment is broadly characterized by the presence of fumes, gases, radiation, heat, and noise in varying amounts. Because of their diverse effects on welder health and safety, these environmental characteristics are reviewed individually below. Arc welding operations are emphasized because of the widespread use of such processes by industry, but the discussion applies equally well to other areas of joining and cutting.

Fumes

Fumes are composed of particulates formed by the vaporization of electrode and base metal constituents in the welding arc. Because they are extremely small, fume particles may remain suspended in the atmosphere for long periods. Since these particles have size and mass, they are affected by air currents, gravity, electrical fields, and other forces. As a result, they tend to agglomerate into clumps that settle on the floor and other surfaces. However, while they are suspended, fume particles can be inhaled by anyone in the welding area. Welding fume particles range in the size of particles that penetrate deep into the respiratory system, but they are generally smaller than particles that are retained with maximum efficiency, unless agglomeration occurs. Significant agglomeration can occur minutes after the fumes are produced.[88]

The hazards presented by welding fumes depend largely on the composition of the fumes and the amount of fumes in the atmosphere. While some fume constituents are merely nuisances, others constitute a definite hazard to the health of welding personnel because of their possible effect on the respiratory and digestive systems.[89-92] To an extent, the presence of specific constituents in the fumes can be predicted on the basis of the composition of the base metal and welding electrode.[a] For example, if a bare carbon steel electrode is used for welding steel, iron oxide will be present as the major fume constitutent along with small amounts of the oxides of manganese and silicon; copper oxide will be present also if the electrode is coated with copper to prevent rusting. Fume constitutents are more difficult to predict if the same steel is welded with a covered or flux-cored electrode. While the oxides of iron, manganese, and silicon will be present in the fumes, constituents associated with the covering or flux will be present also. The presence of such constituents is difficult to predict because of the proprietary nature of electrode coverings and fluxes.

The concentration or amount of fumes in the atmosphere is equally a matter of concern. Fume concentrations are best determined by on-site sampling. Threshold limit values have been established for many chemical substances and physical agents, and numerous fume constituents are included in this listing.[93] The magnitude of the threshold limit value is a relative indication of the hazard presented by specific substances. Fume concentrations can be maintained at acceptable levels by proper ventilation and fume-extracting torches are also effective in controlling fumes.

The background of information on welding fumes is very extensive and only a few items can be cited. Particular attention is directed toward a publication by the American Welding Society that summarizes the results of a 2-year investigation in which determinations were made of the rates at which fumes were produced by a large number of electrodes used for shielded metal-arc welding, gas metal-arc welding, flux-cored arc welding, and gas tungsten-arc welding.[94] This publication also contains similar information on the fumes associated with various cutting and spraying operations. Ventilation requirements for effective fume control are reviewed also. Attention is also directed to the publications of Commission VIII of the International Institute of Welding. This commission is concerned with all aspects of welder health and safety and publishes documents summarizing the results of research conducted by organizations in all parts of the world.

Research in the area of fume control has produced positive results, since electrode manufacturers are conscious of the need to reduce fumes in the welding area. In Japan, for example, studies were conducted to relate the rate at which fumes are produced to the constituents in the coverings on electrodes used for shielded metal-arc welding.[95] Based on the results of these studies, a series of electrodes with low fuming characteristics were developed. In the Soviet Union, the fume generation rate was related to the materials in the fluxes used in self-shielded flux-cored electrodes.[96] Work of a similar nature has also been conducted in the U.S.

Particular care should be observed when coated metals are welded or cut, because constituents of the coatings (zinc, lead, cadmium, etc.) can be hazardous when they are present in the fumes.

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[a] The electrode is the major source of fumes during welding. Base metal contributions to fumes in the atmosphere are relatively small, because the temperature at the surface of the pool of molten weld metal is much lower than that at the tip of the electrode and less fumes are produced as a result.

Gases

Among the various sources for gases in the welding atmosphere are the following: (1) shielding gases, (2) gaseous decomposition products from electrode coverings and fluxes, and (3) gaseous products resulting from reactions of the welding arc with atmospheric constituents and from ultraviolet irradiation of the atmosphere. In common with other gases, the gases produced during welding obey the normal laws of diffusion and mix freely with the atmosphere. They are affected by gravity and air currents, and pass through the respiratory system with other gases in the atmosphere.

As in the case of fumes, the hazards presented by ga es are dependent on the species and concentration in the welding atmosphere. Some gases are relatively innocuous while others produce adverse effects on the health of welding personnel. The presence of specific gaseous constituents can sometimes be predicted by considering the characteristics of the welding process. For example, during gas metal-arc welding, argon may be present in the atmosphere if argon is used for shielding. Argon itself is not hazardous, but welders working in confined areas have been asphyxiated by the displacement of air by argon. Similarly, if carbon dioxide is used for shielding, it may be present along with carbon monoxide, a product formed by the reaction of the arc with carbon dioxide. Gaseous constituents during shielded metal-arc welding and flux-cored arc welding are more difficult to anticipate because of the complex nature of electrode coverings and fluxes. Ozone is another problem gas that is formed by a reaction of the arc on the oxygen in the atmosphere. It can be present during all arc welding operations, however, it is most likely to form during gas tungsten-arc welding, gas metal-arc welding, or plasma arc welding. Welding in the presence of vapors from metal cleaning operations is particularly hazardous, because toxic gases can be produced by reactions with the arc or the radiation associated with the arc.

Concentrations of gases in the welding area are best determined by on-site sampling. In general, adequate ventilation should suffice to reduce concentrations of potentially harmful gases to acceptable levels.

Again, information on the gases present during specific welding operations and their effects on welder health and safety can be obtained in documents published by the American Welding Society and the International Institute of Welding. A few references are also cited in the bibliography.

Radiation and Heat

Welding and cutting operations are accompanied by various types of radiation, each of which is discussed briefly:

- Ultraviolet radiation, both direct and reflected from electric arcs, can produce adverse and painful effects on the eyes and skin. However, few serious problems other than those caused by carelessness are normally encountered if the appropriate and available shaded lenses and protective clothing are worn. Products resulting from the ultraviolet radiation of atmospheric constituents (and contaminants) can be best handled with adequate ventilation. Reflected radiation from ceilings and walls is particularly bothersome, because the welder is often unaware of its occurrence. Radiation of this nature can be minimized by the use of paints and coatings that absorb rather than reflect radiation.

- Visible radiation can produce glare, eyestrain, and discomfort. However, these problems can be effectively eliminated by the use of proper eye protective devices.
- Infrared radiation produced during welding and cutting operations rarely damages the eye because of the protection provided by shaded lenses. However, heat, another manifestation of infrared radiation, can produce burns, fatigue, discomfort, and reduced efficiency. The effects of heat can be minimized by ventilation and the use of protective garments.

An overview of the problems presented by arc radiation is contained in an article by Pattee, et al.[97]

The most current and reliable data on the radiation produced during arc welding and cutting are contained in documents published by the U.S. Army Environmental Hygiene Agency.[98,99] This organization, in cooperation with the American Welding Society, conducted extensive studies to measure the ultraviolet and infrared radiation associated with the following processes: shielded metal-arc welding, flux-cored arc welding, gas metal-arc welding, gas tungsten-arc welding, and plasma-arc welding and cutting. During the course of this investigation, radiation levels were determined as a function of the welding (and cutting) parameters, shielding gas type, etc.

Noise

While noise is rarely a problem during most arc welding operations, air carbon-arc and plasma-arc cutting operations can produce noise at levels exceeding allowable limits. Noise can produce fatigue and discomfort, and the long-term exposure to noise at high levels can result in a loss of hearing efficiency. Such problems can be minimized by the use of ear protection devices. Information on the noise associated with the following processes are contained in an American Welding Society publication: shielded metal-arc welding, gas metal-arc welding, gas tungsten-arc welding, flux-cored arc welding, and air carbon-arc cutting.[100] In these studies, noise levels were determined as a function of current for the various processes.

DEVELOPMENTS IN MECHANIZED WELDING

In contrast to the area of process development where progress has largely occurred as the result of evolutionary changes in various welding processes, significent advances in mechanized welding have been made in recent years, primarily because of pressures in the marketplace, and many more developments are in the immediate offing. The automation of welding processes has been an important objective in the continuing search for improved quality, and many notable advances were made during the years in which the requirements of various space programs had a profound effect on all areas of technology. While progress did not cease when expenditures for space exploration were reduced, research efforts were muted to some extent and a hiatus in automated welding developments occurred as a result. With the need to reindustrialize to meet foreign competition in many areas of our economy, large sums are being expended to increase productivity through the use of highly mechanized welding systems.

Depending on one's perspective, mechanized welding has many connotations. For some, it means the use of sophisticated welding systems and industrial robots. For others, it means the use of semiautomatic and automatic welding equipment in manufacturing applications where joints with fairly simple configurations must be produced in large quantities. The importance of this latter concept should not be denigrated, since many advances in the control of welding operations have occurred as the result of efforts in this area. However, it is one thing to automate a welding process to attach stiffeners to plates for structural applications and quite another to accomplish the same objective in a system designed for the remote repair welding of defective piping in a nuclear reactor or for the production of several hundred high-quality spot welds in an automobile.

Fusion welding operations are inherently difficult to automate because of the interdependence of the process variables. For example, the production of a simple gas metal-arc weld with acceptable quality requires a consistent combination of current, voltage, wire feed, and travel speed to achieve and maintain a state of dynamic equilibrium during the entire welding process. Even if the welding parameters are properly chosen and controlled within close limits, successful welding may be difficult to achieve unless the parts are suitably fixtured and means are provided to assure consistent fitup during welding. Parameter selection itself is not always straightforward, since acceptable welds may be produced with more than one combination of variables. Also, the directly measurable variables may be only indirectly related to the characteristics of the weld. For example, increasing the heat input may eliminate lack-of-penetration defects, but it may also result in a poorly contoured weld bead. In general, resistance welding variables are easier to control than those associated with fusion welding processes, and acceptable parts fitup is easier to achieve as well.

True mechanized welding began with the use of numerical control at the height of the space program, even though this type of control had been used in the machining area for several years. In the case of fusion welding, numerical control presumes that the commands needed to control all equipment and positioning functions can be reduced to numbers and entered on a punched card, perforated tape, etc. Numerical control further presumes that the process variables are well-behaved and will not exceed the tolerances required for the production of acceptable welds. In practice, the numerical data required to direct the welding head along the joint and control other equipment operations are derived by experiment. These data can be manually transferred to punched cards or a perforated tape by means of a machine that resembles a typewriter. Alternatively, the punched cards or perforated tape can be automatically prepared using a computer and previously written programs. In such a case, the required equipment operations are described in a computer language and are entered into the computer.

When a weld is made, a control unit is used to convert the numerical data to electrical signals that govern the movement of the welding head along the joint at the desired rate and initiate other equipment functions such as shielding gas flow, wire feed, etc. The positioning of the welding head with respect to the joint is governed by servo systems that accept signals from the control unit. Feedback systems of various types (e.g., a seam tracking device) can be used to correct the position of the head if it deviates from its prescribed path. Both positioning and continuous-path controllers are used in mechanized welding equipment with some units being capable of controlling several axes of motion.

While acceptable welded joints can be effectively produced with numerically controlled equipment, such a system is not the complete answer to all of the problems associated with fusion welding operation because some variables affecting performance behave unpredictably as welding progresses and the adjustments needed to overcome deficiencies in welding cannot be included in the numerical instructions in advance. Adaptive control systems can be used to handle such variables by means of sensors designed to detect a change in a selected performance criterion and provide the electrical signal required to initiate corrective action during welding. For example, sensors that detect penetration can be used in such a control system. It should be noted that a fusion welding process can be numerically controlled without the use of adaptive controls, but adaptive control is not feasible without some type of numerical control.

This discussion on numerical and adaptive control has been necessarily brief, but more information is readily available in the literature. The numerical control of fusion welding operations is exemplified by computerized equipment designed to repair weld blades and vanes for gas turbine engines[101], to fabricate stiffened panels for hydrofoils[102], and to weld truck axle components[103]. Numerical control has also been applied widely to resistance welding and metal cutting processes. For example, a computerized resistance spot welding system is being used to attach brackets and doublers to large-diameter ellipsoid bulkheads by one aircraft company.[104] The computer automatically selects one of 58 different welding schedules from disc storage and controls ten welding parameters. Then the computer positions the bulkhead and performs thousands of spot welds automatically on the compound surface of the part. Considerable effort has been directed toward the development of adaptive controls for resistance spot welding applications and several firms are using these controls in production. One such in-process feedback control uses acoustic emission techniques to detect the onset of expulsion during the production of spot welds.[105] Once expulsion is detected, current flow is interrupted by control devices to prevent overwelding. Adaptive controls for resistance spot welding equipment that are based on the sensing of current, voltage, input energy, volumetric expansion, thermal expansion, and other parameters have also been developed.

While significant advances have been made in the automation of many welding operations, developments in two specific areas merit special attention: mechanized equipment for the welding of pipe and tubing and welding robots. These topics are discussed in the following sections.

Automated Pipe and Tube Welding Systems

The need to produce highly reliable girth joints in pipe and tubular products for many applications has provided the impetus for the development of several sophisticated welding systems. While some overlapping may occur, these systems can be generally classified as follows:

- Systems designed for the construction of long-distance gas and liquid transmission lines. Pipe sizes handled by such systems range from about 16 to 56 inches in diameter.
- Systems designed for welding joints in small-diameter tubing for applications in the aircraft, missile, nuclear, and other industries. Tubing diameters range from less than 1 inch to about 10 inches. Tubing may be fabricated from any ferrous or nonferrous metal.

Transmission Line Welding Systems

Several automated welding systems have been developed for the construction of pipelines to transport natural gas, crude oil, and other hydrocarbons over long distances. All were developed with the objective of producing high-quality girth welds in large-diameter line pipe at rates in excess of those that could be achieved by a competent crew of manual pipe welders. Some systems have been very successful; others were too complex for use in the field or were not able to withstand the rigors of operation under the conditions encountered in pipe laying.

- CRC-Automatic Welding system has been used successfully to construct several thousand miles of land and marine pipeline. Welding is done with solid filler wire and argon-CO_2 shielding. This system comprised three major pieces of equipment: an end preparation machine that bevels the ends of the pipe, a multihead internal welding machine that deposits the root pass, and several external welding machines that deposit the hot, fill, and cap passes. The internal welding machine is combined with a pneumatic line-up clamp and the external machines are mounted on steel bands that are positioned around the pipe. The operations of the internal machine are programmed and are accomplished automatically without operator supervision. The external welding machines function automatically also but an operator is available to make any required equipment adjustments. Details of overland pipe laying as well as operations from a lay barge are available in the literature along with information on the metallurgical considerations of welding.[106,107]

- H. C. Price System's success has been demonstrated in overland pipe-laying operations and the equipment has also been installed on a lay barge. It features a duplex power supply comprised of a constant-current and a constant-potential unit connected in parallel. By combining the flat and drooping characteristics of these power units, it has been possible to extend the working range for CO_2 welding in the short-circuiting mode. A unique internal line-up clamp provides the means to accurately establish the joint root opening. The clamp also contains a copper backup for the root pass weld. Welding is done from the outside of the pipe with four heads mounted on a yoke assembly that straddles the joint.

Other systems based on the use of flux-cored arc welding, gas tungsten-arc welding, and electron-beam welding have also been developed. However, little or no field experience has been obtained with these systems.

Tube Welding Systems

Extensive efforts have been directed toward the development of automated systems for welding various types of relatively small-diameter tubing whose position is fixed. Much of the early development occurred in the aircraft and aerospace industry where there is a continuing need for high-quality joints in hydraulic and pneumatic tubing systems. However, these systems have proven to be equally useful in the welding of tubing in submarines, nuclear reactors, and other structures. Two basic types of orbiting-arc equipment have been developed, all of which are based on the use of gas tungsten-arc welding: (1) a clam-shell, clamp-on unit with an inner circular rack and pinion drive that rotates a sealed assembly containing the tungsten electrode around the small-diameter tubing joint and (2) a carriage unit containing the welding head, wire feed equipment, and wire reel that rotates around the tubing or pipe on a circular band.

The use of the gas tungsten-arc welding is emphasized in these systems because this process is capable of producing very high-quality welds in a wide variety of base metals. It is probably the most controllable of the arc welding processes and it can be used to make welds in all positions. Welds can be made with or without added filler wire, depending on the wall thickness of the tubing, the joint design, and other considerations. Filler wire can be fed into the molten weld pool area as a cold or hot wire addition.

The features of selected commercially available pipe and tubing welding systems have been reviewed. For the most part, these reviews are based on an examination of the manufacturer's literature.

- Astromatic Systems developed by the Astro-Arc Company are among the oldest and most widely used pipe and tube welding systems. This firm manufactures both of the basic types of orbiting-arc equipment in several versions that encompass a wide range of pipe and tubing sizes. Clamp-on units with interchangeable components (tube clamp inserts, gas cups, and tungsten electrodes) are available for making autogenous welds in thin-wall tubing with diameters of 1/16 to 9 inches; carriage-type systems are provided for welding pipe with diameters of 2 to 56 inches and wall thicknesses as great as 3 inches. Several programmable solid-state power supplies are available for use with these welding systems. They deliver straight or pulsed DC current at several levels of control. Remote operations at 175 feet or more from the power supply are possible with carriage-type units because all manual adjustments can be mechanized. Carriage-type units also include such features as electrode oscillation with dwell, automatic voltage control, wire straightening, and cross bead adjustment. Typical systems are shown in Figures 26 and 27. Astro-Arc offerings also include automated equipment for tube-to-tubesheet welding, internal welding, and other specialized applications.

- Dimetrics Systems developed by Dimetrics, Inc., produces carriage-type systems for internal and external welding operations. The internal unit can be used with pipe and tubing whose inside diameter exceeds 16 inches; pipe and tubing with outside diameters in excess of 2 inches can be welded with the external units. The solid-state power supply pulses the DC output current at 16,000 Hz. Reportedly, this capability results in the production of narrow welds with a fine-grained microstructure. The high-frequency pulsed current can be pulsed at a slower rate, 1 to 10 pulses per second and the wire feed can be pulsed also. Pulsed current, pulsed wire feed, and arc voltage can be synchronized with the electrode oscillator to control the weld bead contour. The oscillator provides variable dwell time at both sides of the bead. In addition to these features, automatic voltage control and cross bead adjustment are provided. All welding operations can be controlled from programming stations that permit remote welding at distances up to 300 feet or more. Dimetrics equipment is shown in Figure 28.

- Hobart Systems developed by Hobart Brothers Company is a system for welding pipe with diameters ranging from 1-1/2 to 5-5/8 inches. It consists of a solid-state power supply with interchangeable programmers, a clamp-on welding head, a motor speed control, and a remote control pendant. Two programmers

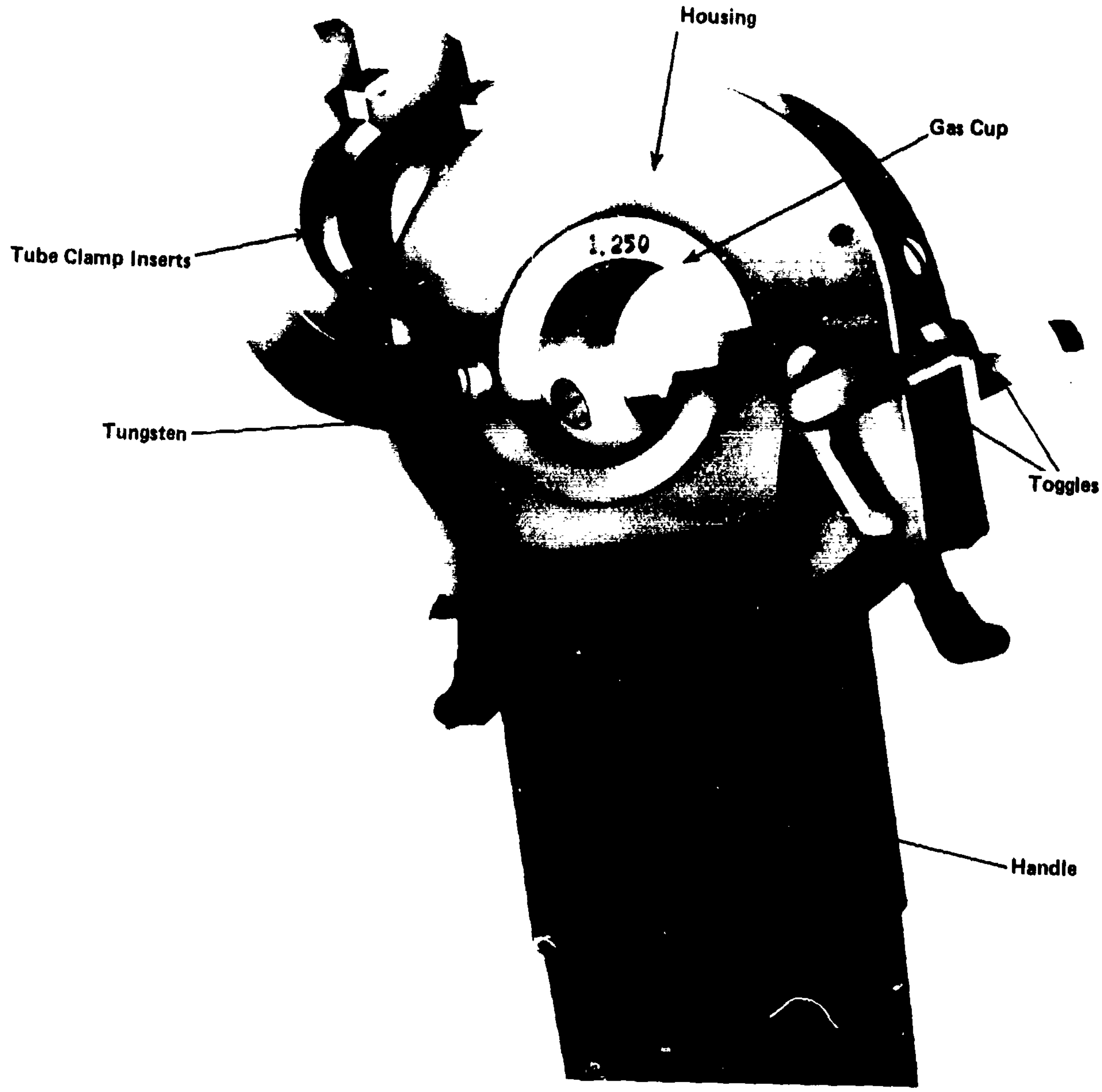

FIGURE 26. Astro-Arc Clamp-On Tube Welding Head

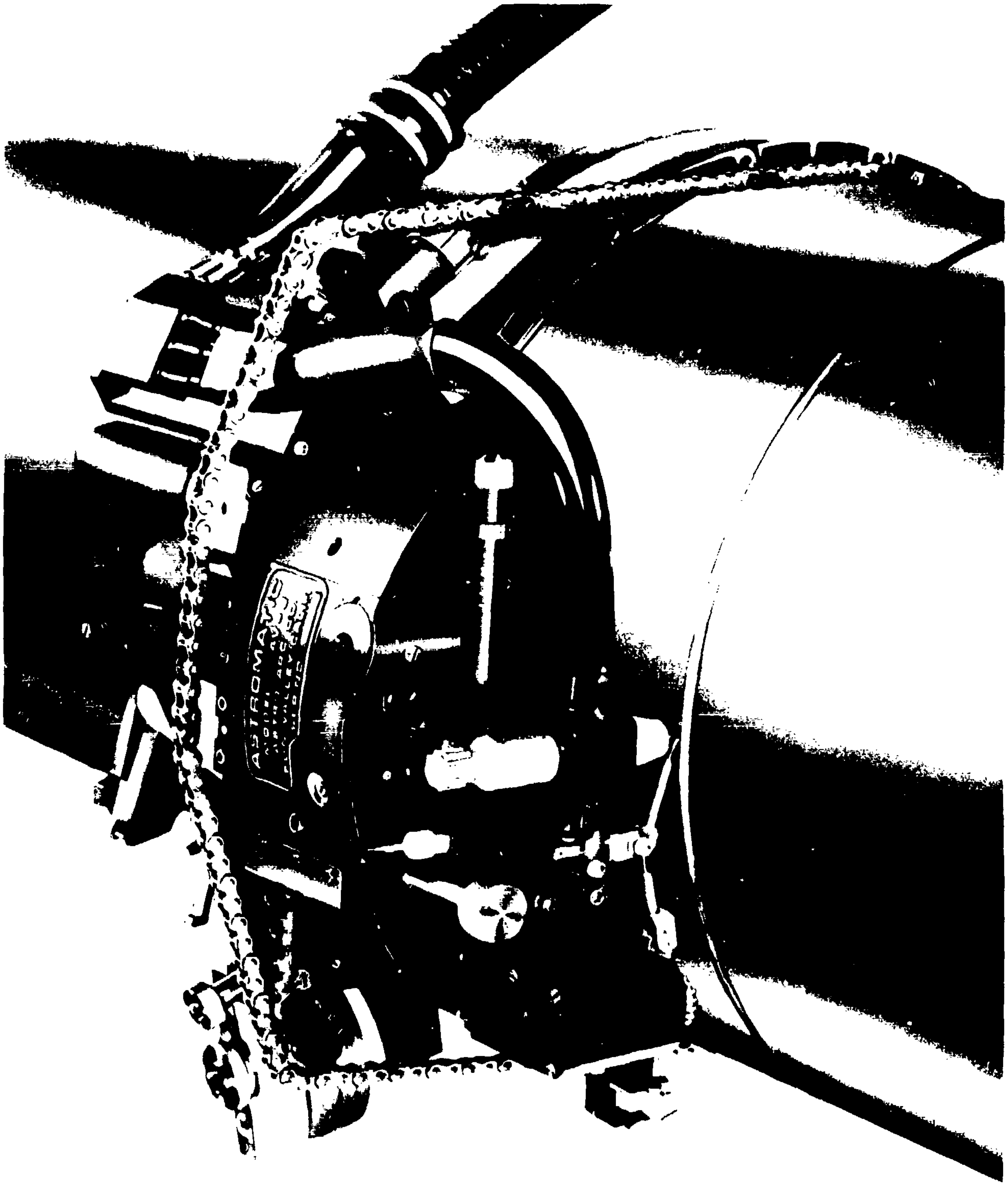

FIGURE 27. Astro-Arc Orbiting GTA Pipe Welder

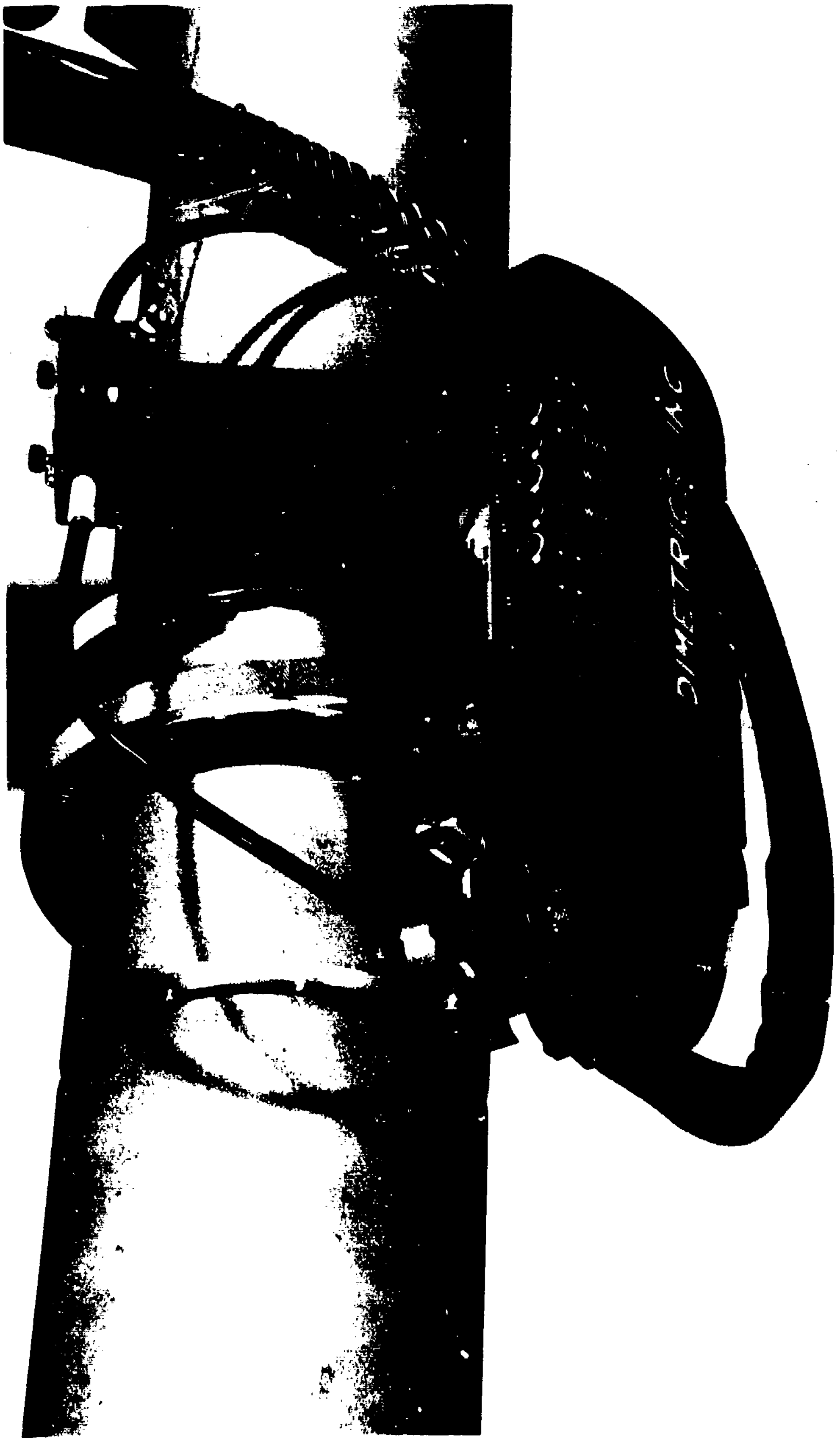

FIGURE 28. Dimetrics Orbiting Pipe Welding Head

are available, one differs from the other by the inclusion of a weld taper in addition to upslope, downslope, and pulsing capabilities. The system for welding pipe and tubing is shown in Figure 29. Hobart also manufactures automatic equipment for tube-to-tubesheet welding.

Orbiting-arc equipment for welding pipe and tubing is also manufactured by Magnetec, Arc Machines, Inc., and by several foreign producers.

Welding Robots

The most significant advance in joining technology in recent years has been the development of welding robots because of the beneficial effect of these devices on productivity and fabrication costs and because of their impact on the manner in which manufacturing will be done in the future. While industrial robots date back to the 1960s, their use for welding represents a new extension of their capabilities. More than 3500 industrial robots have been installed in U.S. production facilities during the past 15 years, and new ones are being installed at an increasingly faster pace in response to the need to reindustrialize our economy. Much of the pressure to use this equipment has been generated by the Occupational Safety and Health Act which imposed restrictions on the human handling of parts in punch presses and other machines with hazardous operating characteristics. Further pressure has been provided by the increasing unwillingness of workers to perform dirty, repetitious tasks. Since robots are easily programmable devices that perceive neither weariness nor boredom and operate under the most trying conditions for three shifts a day, they are ideal candidates for such tasks. As a result, robots are being used for spray painting, many machining operations (grinding, polishing, deburring, etc.), and all types of parts handling in hazardous and nonhazardous environments. They are particularly well suited to the handling of hot parts in forging and casting operations. Most recently, they have been used for resistance and arc welding applications.

The reasons for converting a manual or mechanized-arc welding operation to a robot-arc welding operation are severalfold. Since welding can be conducted at a distance, the robot provides the means to insulate the welder from the potential hazards associated with the welding environments: fumes and gases, radiation and heat, and noise. It also provides the means to improve productivity by optimizing arc time, increasing output, and minimizing rework operations. Also, when one considers that the hourly wages for an assembly-line worker are about \$15 to \$20, the economic incentive to install and use robots can scarcely be ignored. For example, it is estimated that a robot costing \$40,000 can be operated and amortized over an eight-year life for \$5 to \$6 per hour. In many cases, a robot can justify its cost in 2 to 3 years. In the case of arc welding, payoff may be even faster because effective arc time (the actual time in which welding is done) may be tripled by the use of a welding robot.

With respect to welding, industrial robots were first used for resistance spot welding operations in the aircraft and automotive industries, and most of the production welding robots are still concentrated in these areas of manufacturing. Spot welding operations are relatively easy to robotize because of the ease with which the process variables can be controlled and entered into the computer program of a robot. Also, the electrodes can serve to fixture the joint members during welding and weld quality can be assured by in-process monitoring of the welding variables. The development and use of arc welding robots has lagged that of robots designed for spot welding, because arc welding processes are more

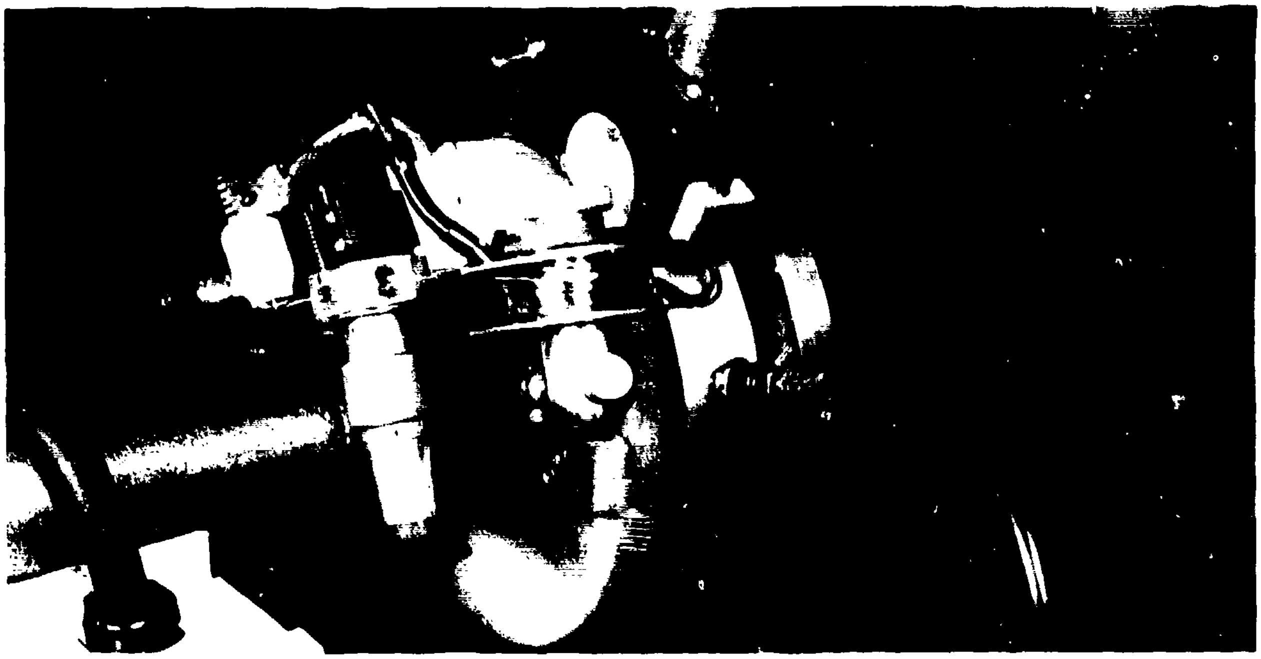

FIGURE 29. Hobart Orbiting Pipe Welding Equipment

difficult to automate and parts alignment is more difficult to achieve and maintain. In addition, many arc welding applications do not lend themselves to the use of robots because of the size of the components or the limited number of assemblies to be welded. Also, adaptive control of arc welding processes is far more difficult to achieve. While position adaptive control can be readily achieved with seam tracking devices, process adaptive control (that is, the control of penetration, bead contour, and other features that characterize an acceptable arc weld) requires much more development. Nonetheless, several arc welding robots are now being marketed. Most perform gas metal-arc welding, but gas tungsten-arc welding robots are available also.

The direct involvement of welding personnel in the development of welding robots cannot be overemphasized. While there are exceptions, the robot manufacturer is frequently concerned only with the production of multi-purpose robots and has little concept of the complexities of welding. Thus, close cooperation between the manufacturer of robots and the manufacturer of welding equipment provides the assurance that the welding robot will perform satisfactorily and that a responsible organization is available for maintenance and consultation.

Welding robots differ widely in their overall capabilities, the number of axes for which motion is provided, and the manner in which the welding operations are programmed, conducted, and controlled. By their very nature, robots are examples of off-the-shelf automation that are designed to be placed on-line with the minimum amount of special engineering and debugging. A welding robot must be flexible enough to handle a variety of welding tasks. However, it must not be so complex as to prove uneconomical in terms of initial operating costs. For example, a welding station in which parts are positioned by an operator may be much more practical than a completely automated station, particularly because a welding robot can service more than one station. As in the case of any robot, the flexibility of a welding robot is enhanced by computer control, because of the logic and computational capabilities of a computer and its ease in interfacing with external devices. The computational capabilities are used to solve the transformation equations required to coordinate the motion of all axes, including control of the path velocity, acceleration, and deceleration. The logic capability permits the realization of other operational features such as branching and conditional functions.

While welding robots are available in several configurations, they basically consist of a manipulator that performs various mechanical operations, a controller that stores information and directs the movements of the manipulator, and a power supply that provides energy to the manipulator.[108] These major components are described briefly:

- The manipulator consists of a base section and an arm comprised of a series of mechanical linkages and joints that are capable of movement in various directions. The linkages and joints are actuated by hydraulic or pneumatic cylinders, hydraulic actuators, and electric motors. Feedback devices (limit switches, potentiometers, tachometers, resolvers, encoders, etc.) are included to sense the positions of the various linkages and joints and feed this information back to the controller. The feedback data is digital or analog depending on the type of sensing device.
- The controller, a minicomputer in the case of welding robots, initiates and terminates the motions of the manipulator arm by interfacing with the manipulator's control valves and feedback devices. It also stores position and sequence data in its memory and performs complex arithmetic functions to control the path, position, and speed of the welding head. It interfaces with the outside world to provide two-way communication between the controller and various ancillary devices.
- The power supply provides energy to operate the various actuators of the manipulator. That is, the electrical actuators and other devices are driven by electrical power, the pneumatic actuators are driven by air supplied by a compressor, and the hydraulic actuators are driven by fluid supplied by a hydraulic system.

The motions of the manipulator are dependent on the design requirements. In robots designed for welding, the single-piece or jointed arm rotates around the base of the manipulator, moves in and out, and moves up and down. The envelope encompassing these motions approximates a portion of a sphere. Additional motions are provided by the wrist or swivel to which the fixture that holds the welding head or resistance spot welding electrodes is attached. The wrist rotates in the x-y plane, the y-z plane, and the x-z plane to provide the motions of roll, pitch, and yaw, respectively. If the robot must track an assembly during welding, the entire unit can be mounted on a track. Other required motions can be obtained by mounting the unit on an x-y table. The envelope prescribed by a typical 6-axis robot is shown in Figure 30.

A programmable minicomputer is used to initiate, control, and terminate the required welding functions as well as control the manipulative movements of the arm and wrist of the robot; it also stores positioning and sequencing data, performs the calculations required to guide the welding head along its designated path at the proper velocity, and interfaces with various external devices and peripheral equipment. Most systems incorporate provisions for point-to-point and/or continuous-path programming. In some systems, point-to-point is

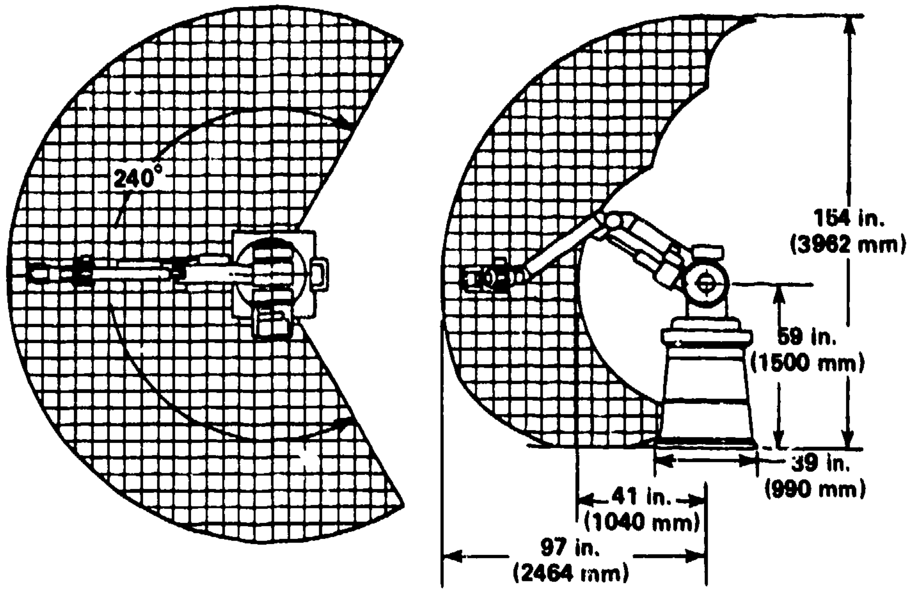

FIGURE 30. Working Envelope Prescribed by Motions of 6-Axis Robot[109]

almost the same as continuous path because the individual points are spaced only a fraction of an inch apart. Position data can be acquired and stored in the memory by manual movement of the welding head along the joint. These data can be also obtained by using a control box to direct the movement of the head along the joint. In some instances, position data for straight or radiused movements can be generated by the computer itself with the appropriate software. Details on programming welding robots are available in the literature.[108-110]

With the foregoing as background, the characteristics of several commercially available welding robots are reviewed briefly in the following sections. The respective manufacturers should be contacted for more information on programming facilities and procedures, optional add-on equipment, and other features.

- Advanced Robotics Corporation markets two computerized, numerically controlled units that differ in the size of the envelope prescribed by the single-piece arm and wrist of the robots (Figure 31). These are 5-axis robots whose movements are powered by DC servomotors with position encoders and tachometer feedback. They can be equipped for gas metal-arc and gas tungsten-arc welding. The overall welding operations are controlled by a minicomputer that decodes the programs and computes the servomotors' position and speed to execute the commands of the program. It also controls the initiation and termination of all welding functions (current, voltage, wire feed rate, torch oscillation, etc.). The servomotors are controlled by a microprocessor. The computer program can be established by jogging the welding head to each successive point on the welding path. Facilities for off-line programming are also provided.

  A Canadian firm has established a production line in which 18 of these robots have been installed to weld the component parts of 6 families of axle housings whose dimensions vary in accordance with the load ratings.[111] Sixteen robots with gas metal-arc welding capabilities have been installed at 6 welding stations; two

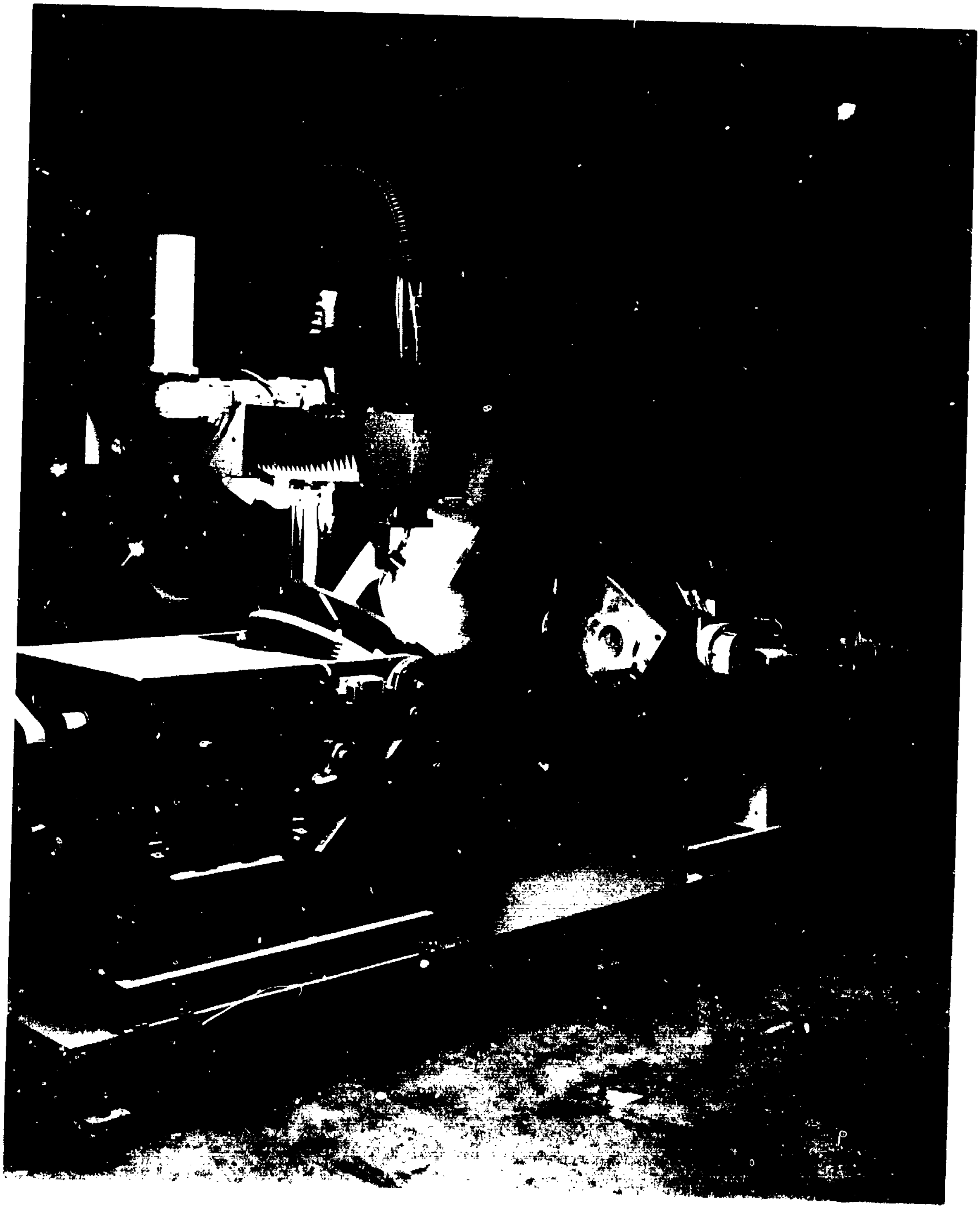

FIGURE 31. Advanced Robotics Arc Welding Robot

additional units equipped with air carbon-arc torches are used to bevel the seam edges of the joint members. The program is prepared by moving the welding head along the welding path to teach the path coordinates to the robot control minicomputer and numerical control commands control the welding process variables and the required tooling actions. Programs for welding the various types and sizes of axle housings are stored on magnetic tape.

- Unimation Systems are marketed by Unimation, Inc., currently the largest producer of robots in this country. The company manufactures a line of industrial robots for a wide variety of assembly and materials handling operations which differ in their reach and load-carrying capabilities. These robots are available with 3 to 6 axes of motion and the arms are not jointed. They can be equipped for gas metal-arc welding, gas tungsten-arc welding, resistance spot welding, and other related operations. Point-to-point or continuous-path programming is used to establish the welding path. All positioning and sequencing data are stored in the computer memory along with data to control the welding process and the movements of the welding positioner. A typical welding robot is shown in Figure 32.

  In the resistance welding configuration, these robots are used extensively for a myriad of spot welding applications in the automotive industry. Unimation robots with gas metal-arc welding capabilities are being used to fabricate the frames of warehouse package carts(112) and to assemble the structural members of traction-motor housings for self-propelled rail vehicles.(113) Fabrication time in the latter application was reduced by a factor of three by the use of robot welding. With a change in tooling, this robot was also used for a machining operation.

  Unimation, Inc., also produces a lightweight, inexpensive arc welding robot with 5 axes of motion that can be readily moved from one work site to another. It was developed for shipyard welding but should be equally useful in many other welding applications.

- Cincinnati Milacron Systems are manufactured by Cincinnati Milacron, currently the second largest manufacturer of robots in this country. The company also produces computer-controlled industrial robots with resistance spot welding and gas metal-arc welding capabilities. These robots are available with a jointed arm and 6 axes of motion. As in other systems, the integrated arc welding system consists of the robot, programmable weld positioner, wire feeder, power supply, and arc welding software. The robot computer controls the position, orientation, and velocity of the welding head in coordination with the movements of the positioner. Point-to-point programming is readily accomplished with a small, hand-held control unit that commits positioning and other data to the computer memory. Digital-to-analog signal converters are used to control wire feed and arc voltage and a weld bead weave function is available for welding wide joints. A welding unit is shown in Figure 33.

  As in the case of other robots, this unit is used widely for resistance spot welding in the automotive industry. In a typical production application, four robots track a car body and produce 244 spot welds at the rate of 48 bodies per hour and a fifth robot is used to establish the required welding programs.(114) Arc welding applications include the fabrication of backhoe buckets and the production of aluminum housings for electronic assemblies.

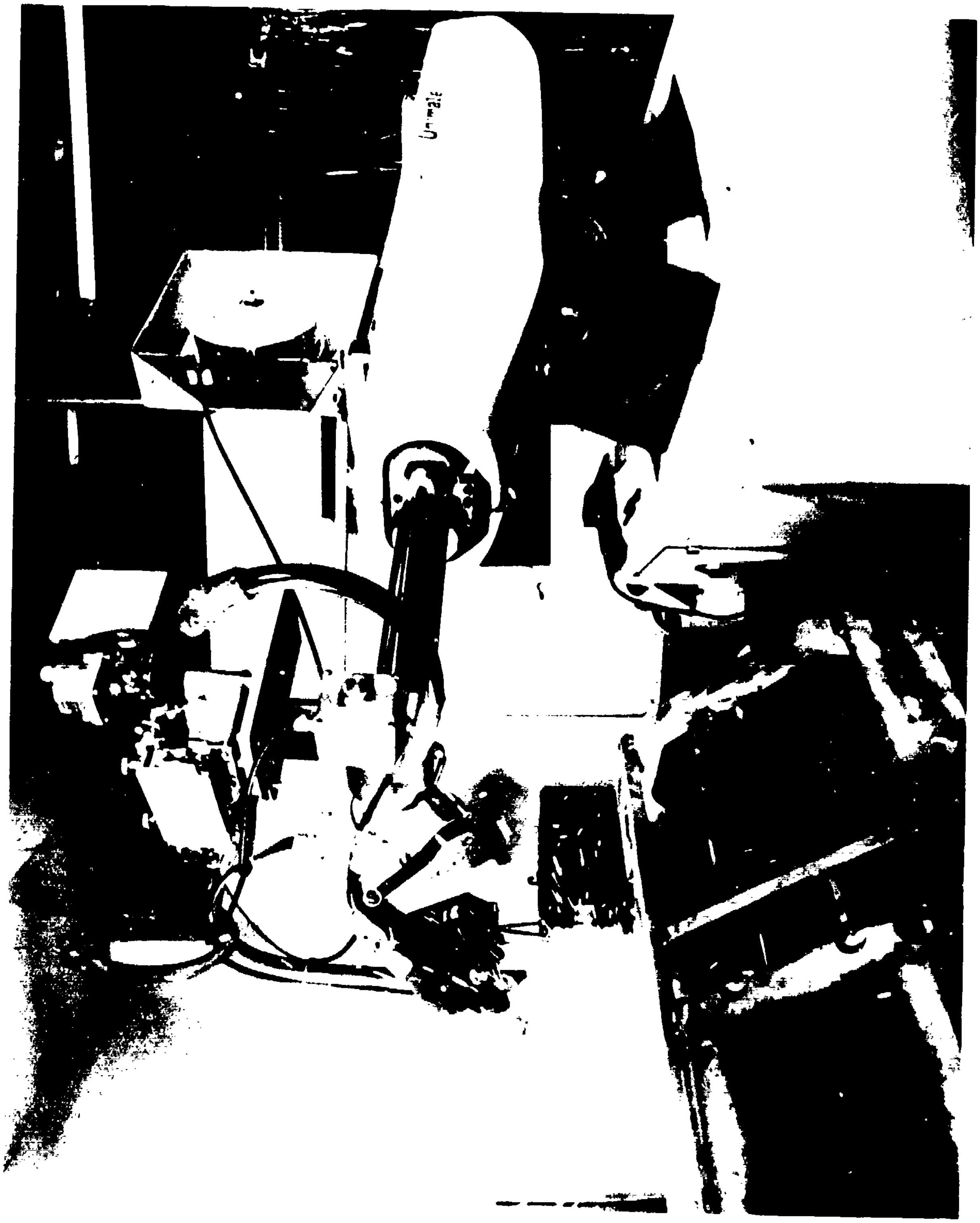

FIGURE 32. Unimation Arc Welding Robot

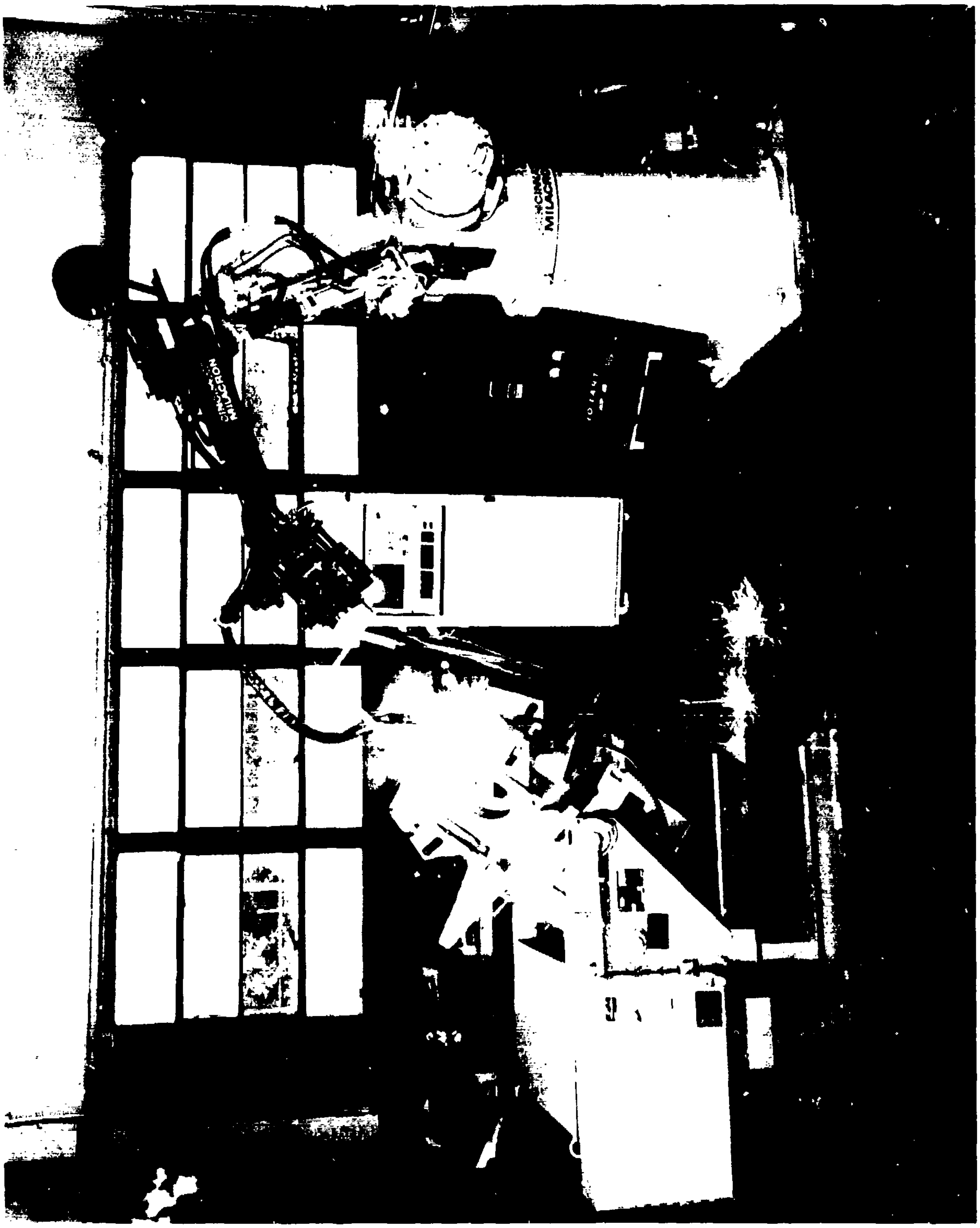

FIGURE 33. Cincinnati Milacron Arc Welding Robot

In all cases, it should be noted that one programming unit can be used to develop a welding program that can be used by several robots. Also, there is wide range of peripheral equipment that can extend the capabilities of these robots.

Other resistance and arc welding robots are produced in this country by ASEA, Inc., Automatix, Inc., and others. Robots have also been designed and constructed by large firms for in-house welding applications. Robots produced by foreign manufacturers are also available.

The market for industrial robots in this country is expanding at a rate sufficient to strain the capacity of the manufacturers to meet current and projected demands. While estimates vary widely, it appears likely that the number of robots in production facilities will increase by a factor of 5 or 6 in the course of this decade. It is expected that the proportion of industrial robots dedicated to welding applications will increase at an even faster rate as the benefits associated with the use of this equipment become more widely recognized. Increased productivity is the underlying reason for the acceptance of industrial robots. However, the impact of such equipment on the quality of manufacturing operations must not be minimized because robots bring the goal of zero defects within reach. By its very nature, a robot can perform many tasks with equal facility and its functions can be reprogrammed readily. As a result, it is well suited to manufacturing operations that are subject to change in response to customer requirements.

While the performance of current robots is impressive, extensive research is being conducted to extend robot capabilities by including the senses of touch and sight. Vision is generally considered to be the key to the next generation of robots and some success has been achieved in the development of visionary systems with real-time response characteristics. Considerable success has also been achieved in the production of systems that can differentiate between parts. Articles citing recent developments in sensory devices are included among the references in this report.[115-119] Some of these devices may be applicable to welding robots.

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