

**RECOMMENDED  
PRACTICES  
FOR PLASMA-ARC  
WELDING**

AMERICAN WELDING SOCIETY

AWS C5.1-73

# **RECOMMENDED PRACTICES FOR PLASMA-ARC WELDING**

Prepared by  
AWS Arc Welding and Arc Cutting Committee

Under the Direction of  
AWS Technical Activities Committee

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## Foreword

Plasma-arc welding was introduced as a practical fabricating process approximately fifteen years ago. Early applications involved melting, cutting, and spray-coating metallic materials. In the past several years, rapid advances have been made in the development of this technique, and plasma-arc welding has now achieved acceptance as an efficient metal joining process.

During the recent period of progress, sufficient data have been gathered and organized to yield an authoritative source of technical information on plasma-arc welding. Accordingly, the AWS Arc Welding and Arc Cutting Committee has prepared these recommended practices through the work of the Subcommittee on Plasma-Arc Welding. These recommended practices are based on a survey of plasma-arc welding as used in the metal fabricating industry.

The description of plasma-arc welding and its salient features is presented here as clearly and concisely as possible. Because the plasma-arc process is similar to gas tungsten-arc welding, similarities in the processes are not described in detail, to keep the text as brief as possible. The plasma-arc welding process, however, does have unique features in operation and equipment that are advantageous for a certain range of metal thicknesses. These features are fully explored in the text.

The Committee developed these guidelines in the hope that they would lead to further development of the plasma-arc welding process and thus to higher quality and performance standards. Comments on this publication will be most welcome. They should be addressed to the Secretary, AWS Arc Welding and Arc Cutting Committee, American Welding Society, 2501 N.W. 7th Street, Miami, Florida 33125.

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# RECOMMENDED PRACTICES FOR PLASMA-ARC WELDING

## 1. Scope

**1.1** These recommended practices present a description of the plasma-arc welding process and practical procedures as applied to joining parts and surfacing. These discussions apply to a wide variety of metals and represent methods used in industry.

## 2. Definitions of Terms\*

**2.1 General.** Some of the terms used in describing plasma-arc welding are the same as those used in gas tungsten-arc welding. Other terms listed are peculiar to the plasma-arc welding process. Many of these terms are shown in Fig. 1.

**2.2 Plasma arc.** A plasma—a gas heated to a condition of at least partial ionization that is capable of conducting electric current—exists during any arc occurrence. In nature, the gas ionized by a lightning bolt constitutes a plasma. The same ionization phenomenon occurs in welding arcs, carbon-arc lights, and arc furnaces. In recent years, however, the expression “plasma arc” has become associated with those processes employing a constricted arc. Arc constriction is brought about by forcing the arc to pass through a small nozzle or opening as it passes from the electrode to the workpiece.

**2.3 Plasma-arc welding.** An arc welding process wherein coalescence is produced by heating with a constricted arc between an electrode and the workpiece (transferred arc) or the electrode and the constricting nozzle (nontransferred arc). Shielding is obtained from the hot, ionized gas issuing from the orifice which may be supplemented by an auxiliary source of shielding gas. The shielding gas may be inert or a mixture of gases. Pressure may or may not be used, and filler metal may or may not be supplied.

**2.4 Constricted arc.** An arc column shaped by a constricting nozzle orifice.

**2.5 Constricting nozzle.** A water-cooled copper nozzle surrounding the electrode and containing the constricting orifice.

**2.6 Constricting orifice.** The hole in the nozzle through which the arc passes.

**2.7 Double arcing.** A condition in which the main arc does not pass through the constricting orifice but transfers to the inside surface of the nozzle. A secondary arc is simultaneously established between the outside surface of the nozzle and the workpiece. Double arcing usually damages the nozzle.

\*For AWS terms and definitions, refer to the latest edition of publication AWS A3.0, Terms and Definitions. Please note that some of the terms and definitions used in this publication are not included in AWS A3.0. They are either new terms defined after the last revision of A3.0 or they are used to clarify this publication.

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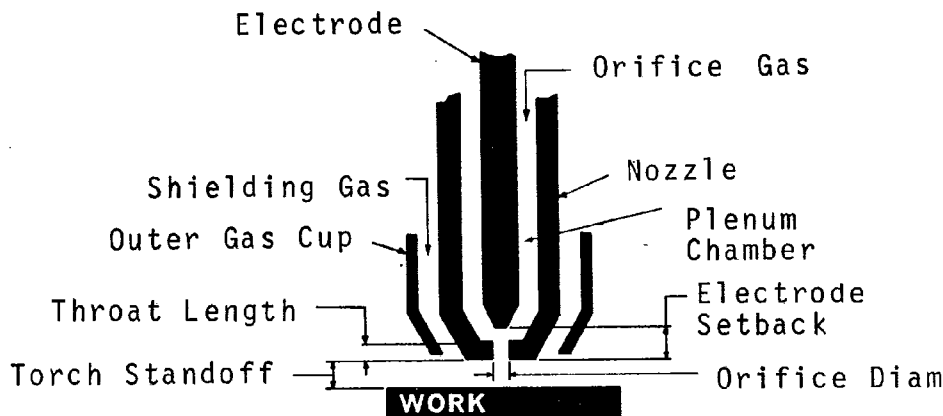


Fig. 1 - Plasma-arc torch terminology.

**2.8 Electrode setback.** The distance the electrode is recessed behind the constricting orifice measured from the outer face of the nozzle.

**2.9 Keyhole.** A condition in which the plasma column penetrates completely through the workpiece at the leading edge of the weld puddle. As the torch progresses, the molten metal, supported by surface tension, flows in behind the keyhole to form the weld bead.

**2.10 Lack of fill.** Slight and blending reduction of thickness at the toe(s) of the weld generally associated with keyhole-type welds.

**2.11 Multiport nozzle.** A constricting nozzle containing two or more orifices located in a configuration to achieve a degree of control over the arc shape.

**2.12 Nontransferred arc.** An arc established between the electrode and the constricting nozzle. The workpiece is not in the electrical circuit.

**2.13 Orifice gas.** The gas directed through the plenum chamber and constricting orifice to form the plasma column.

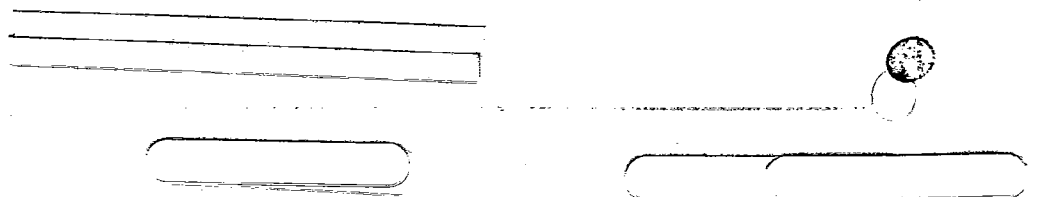
**2.14 Pilot arc.** A low-current arc established between the electrode and the nozzle to ionize the orifice gas and facilitate starting the main welding arc.

**2.15 Plenum or plenum chamber.** The space between the inside wall of the constricting nozzle and the electrode.

**2.16 Shielding gas.** A protective gas provided at the outer periphery of the arc to prevent air contamination of the weld and/or base metal.

**2.17 Single port nozzle.** A constricting nozzle containing one orifice, located below and concentric with the electrode.

**2.18 Throat length.** The length of the constricting orifice.



**2.19 Torch standoff.** The distance from the bottom of the constricting nozzle to the workpiece.

**2.20 Transferred arc.** An arc established between the electrode and the workpiece.

### 3. Fundamentals

#### 3.1 Process Description

##### 3.1.1 General Description

**3.1.1.1** The distinguishing feature of the plasma-arc welding process lies in the use of a constricting orifice. Arc constriction by a nozzle brings about several changes in arc characteristics. The most important of these is that the arc can be projected as a stream of ionized gas similar to a water stream from a hose nozzle, with strong directional stability.

##### 3.1.2 Arc-Constricting Nozzle

**3.1.2.1** A wide variety of nozzles has been made and evaluated. These include the single port nozzles and multiport nozzles with holes arranged in

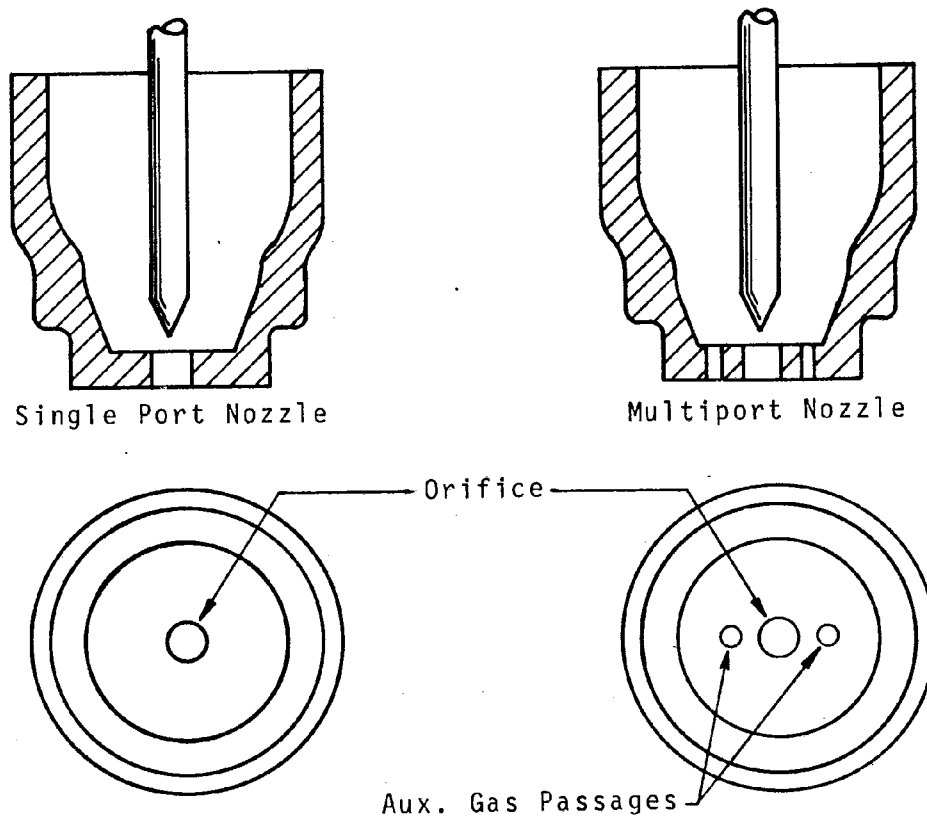


Fig. 2 - Single port and multiport nozzles.

circles, rows, and other geometric patterns. The single port nozzles are most widely used. Among the multiport nozzles, the most widely used design is the one in which the center orifice is bracketed by two smaller ports, with a common centerline for all three openings. These more common nozzle types are shown in Fig. 2.

**3.1.2.2** The electrode in the plasma-arc torch is recessed in the arc-constricting nozzle. As the arc passes through the nozzle, it is collimated and focused so that the arc heat is concentrated on a relatively small area of the workpiece. This increased heat concentration, coupled with the characteristically more forceful plasma stream, can produce a narrower weld fusion zone in a certain range of metal thicknesses.

**3.1.2.3** With the single port nozzles, the arc and all of the orifice gas pass through the single orifice. With the multiport nozzle shown in Fig. 2, the arc and some of the orifice gas pass through the larger center orifice, while the remainder of the orifice gas is discharged through the two smaller ports that bracket the center orifice. The effect of the gas flow from the side ports is to squeeze the cross section of the circular plasma-arc column into an oval or elongated shape. This is particularly desirable in keyhole-mode welding.

### **3.1.3 Keyhole-Mode Welding**

**3.1.3.1** In plasma-arc welding of certain metal thicknesses special combinations of plasma-gas flow, arc current, and weld travel speed will produce a relatively small weld puddle with a hole penetrating completely through the base metal at the leading edge of the weld puddle (called the keyhole). The plasma-arc process is the only gas-shielded welding process with this unusual characteristic.

**3.1.3.2** In a stable keyhole-mode operation, molten metal is displaced to the top bead surface by the plasma stream (in penetrating the plate) to form the characteristic keyhole. As the plasma-arc torch is mechanically moved along the weld joint, metal melted by the arc is forced to flow around the plasma stream, along the molten side surfaces of the keyhole and to the rear where the weld puddle is formed and solidified. This motion of molten metal, and the complete penetration of the metal thickness by the keyhole allow gases and impurities to flow to the surface or be expelled more readily before solidification. This action is similar to "magnetic stirring" developed for gas tungsten-arc welding. The maximum weld puddle volume and the resultant root surface profile are largely determined by the effects of a force balance between the molten weld metal surface tension and the plasma stream velocity characteristics. The bead appearance for a butt weld made in the keyhole mode is pictured in Fig. 3.

**3.1.3.3** With appropriately designed weld joints, the multiport nozzle shown in Fig. 2 can be used to advantage. When the multiport nozzle is aligned to place the common centerline of the side ports perpendicular to the weld groove, the arc is elongated in line with the joint. This allows an increase of keyhole-mode welding speeds of from 30 to 50% over those obtained with single port nozzles, without undercutting and with welds having narrower fusion and heat-affected zones.

### **3.1.4 Comparison of Nonconstricted and Constricted Arcs**

**3.1.4.1** Typical electrical and thermal differences between constricted and nonconstricted arcs are shown in Fig. 4. The schematic representation of a



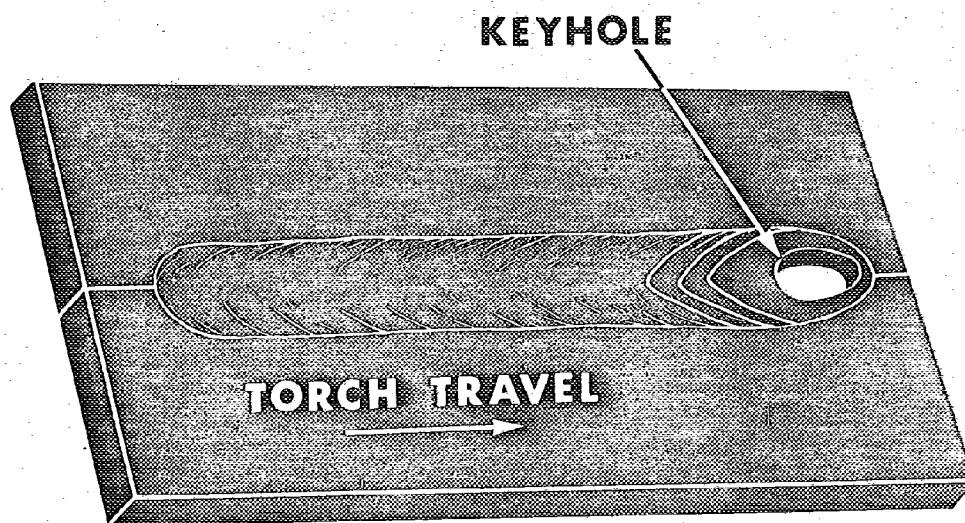


Fig. 3a - Pictorial representation of the keyhole effect.

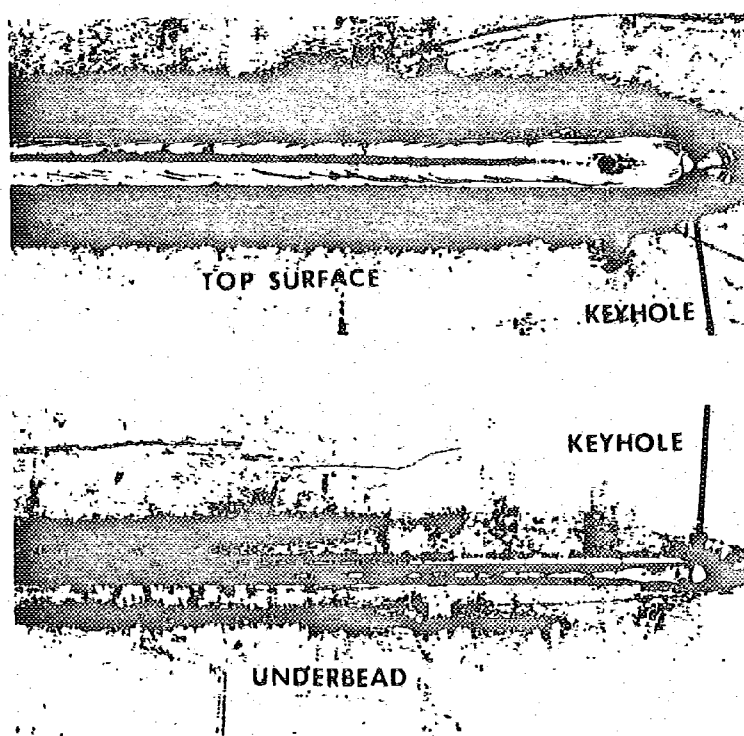
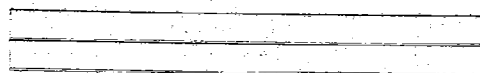


Fig. 3b - Top and bottom view of a keyhole-mode weld on 0.25 in. thick plate.



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nonconstricted gas tungsten-arc is shown on the left side of the figure. Arc conditions are 200 amperes (A) at 15 volts (V) with 40 cfh of argon. The right side of Fig. 4 is a schematic view of a tungsten-arc that has been constricted by passing it through a 3/16 in. diameter orifice. Note that, with the same current and gas flow, arc voltage doubles to 30 volts. Note also that the very high temperature zones of the arc have been projected downward where they can be directly applied to the workpiece. Constricting the arc tends to concentrate the arc energy over a smaller area of the workpiece because the constricted arc does not have the angle of divergence of the nonconstricted arc.

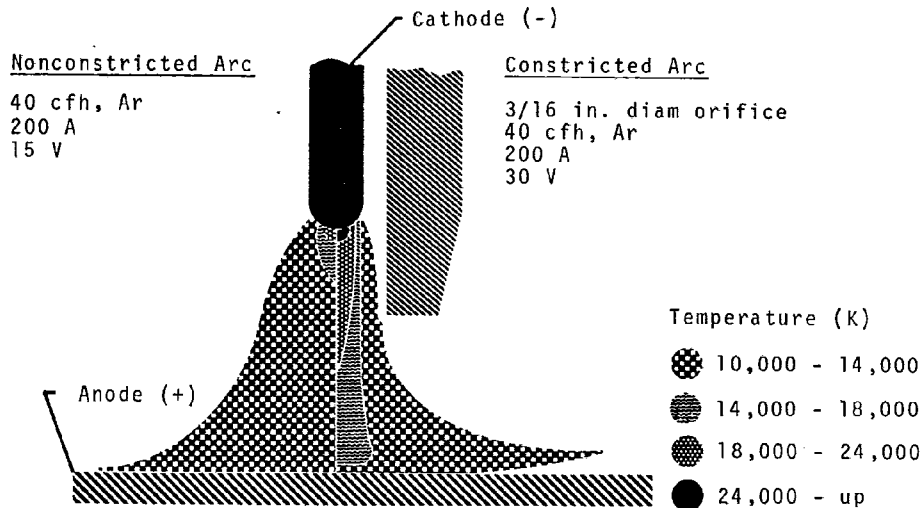


Fig. 4 - Effect of arc constriction on temperature and voltage.

### 3.1.5 Arc Modes

**3.1.5.1** Two arc modes are used in plasma-arc welding: transferred arc and nontransferred arc. With a transferred arc, the arc is established between the workpiece and the electrode within the torch. With a nontransferred arc, the workpiece is not in the arc circuit; the arc is established between the constricting orifice and the electrode inside the torch. Transferred arcs have the advantage of greater energy transfer to work, but they require an electrically conductive workpiece. Nontransferred arcs are useful for cutting and joining nonconductive workpieces or when lower energy concentration is desirable. Figure 5 illustrates the two modes of arc transfer.

### 3.2 Principles of Operation

#### 3.2.1 Manual Plasma-Arc Welding

**3.2.1.1** Manual plasma-arc welding was developed to obtain a stable, controllable arc for welding thin gage metal. It combines a continuously operating pilot arc within the torch for positive welding current initiation, and transferred arc

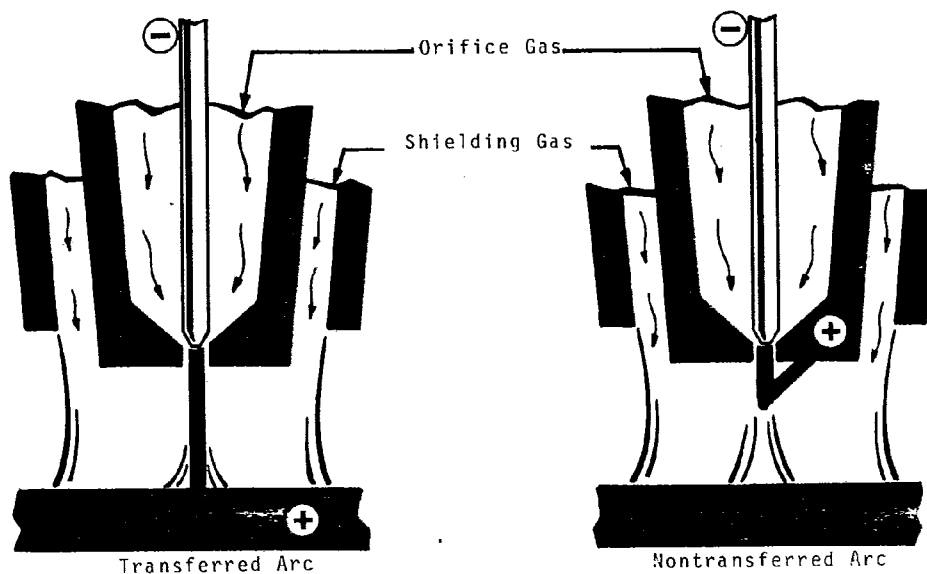


Fig. 5 – Modes of plasma generation: left, transferred arc; right, nontransferred arc.

constriction to provide a stable arc at currents as low as 0.1 ampere. The manual process is well adapted to welding metal thicknesses up to 0.125 in. The low-current volt-ampere (VA) characteristics of the plasma arc operating in argon are shown in Fig. 6. Note that the slope of the low-current plasma-arc VA curve is essentially flat in this range.

**3.2.1.2** A needle-like plasma jet is obtained by passing a low-current arc through a small diameter orifice. The low-current plasma jet has good directional properties and heat concentration, excellent arc stability, and reduced sensitivity to variations in torch-to-work spacing.

**3.2.1.3** A typical electrical circuit for low-current manual plasma-arc welding is shown in Fig. 7. Note that the system utilizes two separate power supplies—one for the pilot arc and one for the transferred arc.

### 3.2.2 Mechanized Plasma-Arc Welding

**3.2.2.1** Mechanized plasma-arc welding utilizes a transferred, constricted arc and is generally operated with high current. Figure 8 illustrates the general characteristics of a typical high current plasma-arc welding system, as well as the electrical circuit used. A direct current (dc) power supply is used to furnish the welding current, and a high frequency generator is used to initiate a pilot arc between the electrode and the constricting nozzle. A current-limiting resistor and condenser network completes the electrical circuit to the power supply.

**3.2.2.2** As the orifice gas passes through the torch to the work, it is heated by the arc, expands and passes through the arc-constricting nozzle at an accelerated rate. The plasma-gas flow range usable for welding is limited because too forceful a plasma stream can cause plasma cutting. This orifice-gas flow alone is not adequate to protect the molten puddle from atmospheric contamination. Auxiliary

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shielding gas is needed and is provided through an outer gas nozzle on the torch. See 5.12 for typical orifice- and shielding-gas flow rates.

### 3.2.3 Powder Surfacing

**3.2.3.1** This fully mechanized application of the plasma-arc welding process utilizes a constricted arc torch and filler metal in powder form. The application is shown schematically in Fig. 9. In addition to the orifice- and shielding-gas supplies used in plasma-arc welding, the surfacing application requires a third gas flow to convey the powdered filler metal from a storage hopper to the torch. Argon is generally used for all three gas systems.

**3.2.3.2** The gas-borne powder is introduced into an annular powder chamber in the torch that uniformly distributes the powder into the arc immediately beneath the arc-constricting orifice. After entering the arc, the powder particles are heated and deposited on the workpiece. These particles are completely melted upon contacting the weld puddle, thus forming a homogeneous deposit, fusion-bonded to the workpiece.

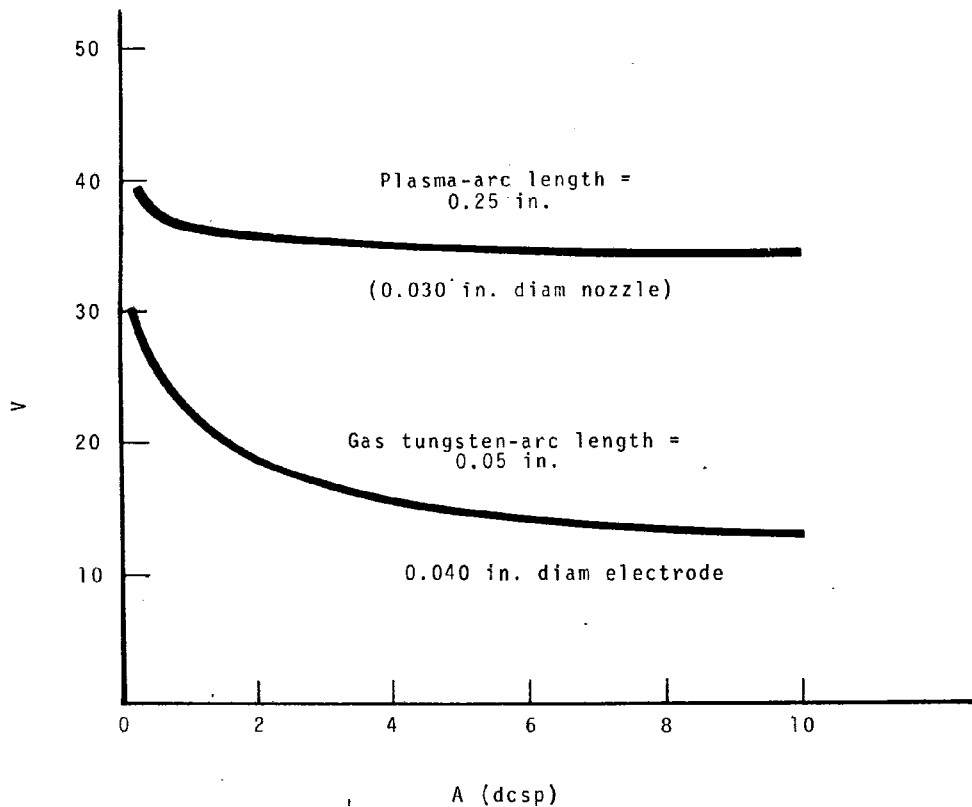


Fig. 6 - Low-current plasma-arc volt-ampere (VA) characteristic curves at arc currents below 10 A in argon.

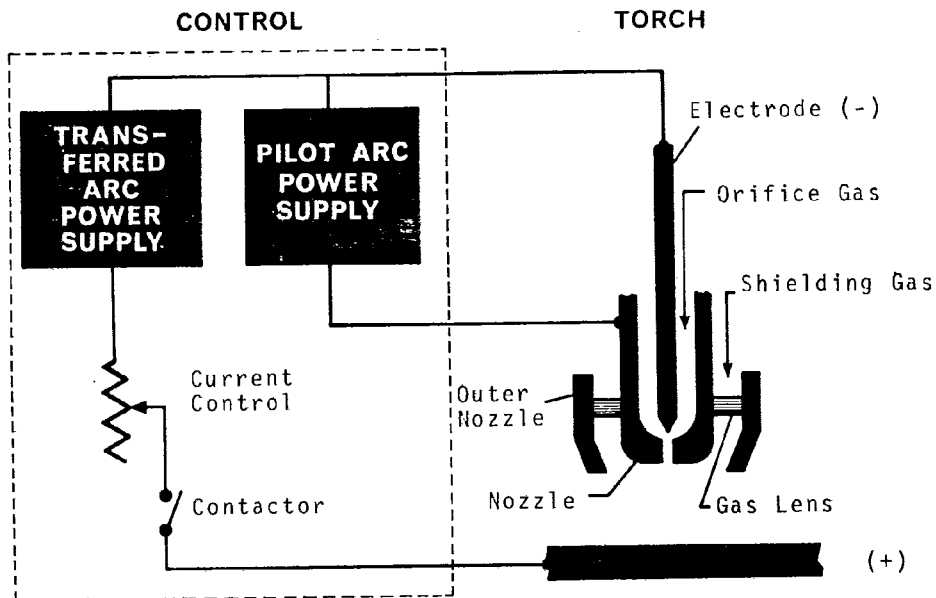


Fig. 7 - Schematic representation of low-current manual plasma-arc welding.

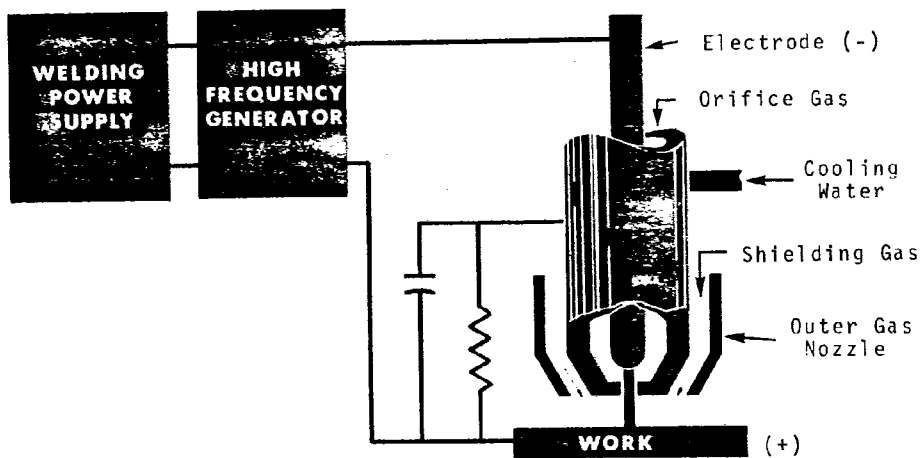


Fig. 8 - Schematic representation of mechanized plasma-arc welding system.

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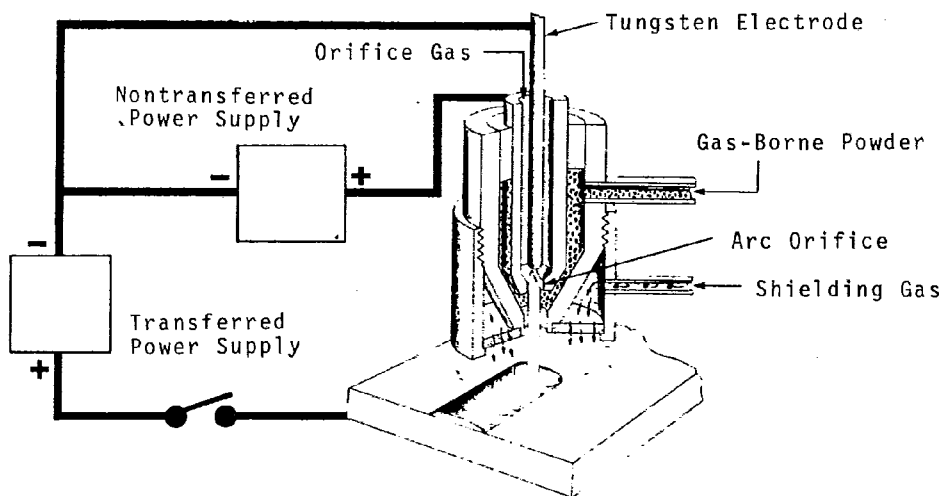


Fig. 9 – Schematic representation of powder surfacing with the plasma-arc welding process.

### 3.2.4 Hot-Wire Surfacing

**3.2.4.1** In the application of the plasma-arc welding process to hot-wire surfacing, filler metal in wire form is resistance heated and deposited on the workpiece in the puddle formed by a plasma-arc torch. This application is shown schematically in Fig. 10.

**3.2.4.2** The electrical circuit and apparatus used for plasma-arc surfacing are similar to the requirements for plasma-arc welding.

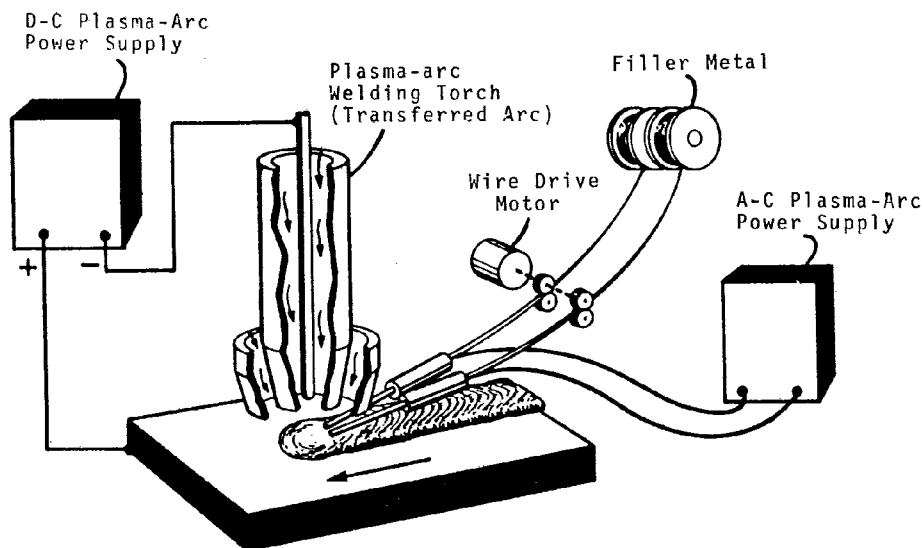


Fig. 10 – Schematic representation of hot-wire surfacing with the plasma-arc welding process.

## 4. Equipment and Apparatus Requirements

### 4.1 Manual Welding

#### 4.1.1 General Requirements

**4.1.1.1** A complete system for manual plasma-arc welding consists of a torch, control, power supply, orifice- and shielding-gas supplies, source of cooling water, and accessories such as foot switch, rheostat, timers, and remote current controls. Apparatus is presently available for operation with low welding current of 0.1 and high of 100 amperes. Development of higher range torches and power supplies has begun.

#### 4.1.2 Power Supply

**4.1.2.1 Transferred Arc Power Supply.** Rectifier type power supplies with a drooping VA characteristic are generally used for plasma-arc welding.

**4.1.2.2 Pilot Arc Power Supply.** Pilot arc supplies are preset to deliver approximately 5 A continuously to provide a stream of ionized gas for instant ignition of the main welding current.

#### 4.1.3 Control Unit

**4.1.3.1** Incorporated in the control unit are the main power supply, pilot arc supply, flowmeters, solenoid valves for controlling orifice and shielding gases, and water flow. Indicating current meters, control switches, and connections for remote current control are generally available.

#### 4.1.4 Torches

**4.1.4.1** Low current plasma-arc torches are lightweight and designed primarily for manual welding. A supply of cooling water at a flow rate of about 1 qt/min and 40 psi input pressure is necessary to dissipate heat generated in the constricting nozzle by the pilot and main welding arcs. The tungsten electrode is automatically centered in relation to the constricting orifice by a ceramic bushing. Auxiliary shielding gas is supplied through a separate gas system. Some manual plasma-arc welding torches are available for operation on direct current straight polarity (desp) at currents up to 225 amperes. Standard torch holders can be used to mount the torch for mechanized use.

#### 4.1.5 Filler Metal

**4.1.5.1** Filler metal can be added during manual welding in the same manner as during gas tungsten-arc welding. Wire diameters should be of suitable size for the currents used. See 5.3.

#### 4.1.6 Gases

**4.1.6.1** See 5.4.

### 4.2 Mechanized Welding

#### 4.2.1 General Requirements

**4.2.1.1** Mechanized equipment must be used to achieve the welding speed and penetration advantages associated with high current plasma-arc welding. A mechanized installation consists of a power supply, control unit, welding torch, torch stand or carriage, cooling water pump, high-frequency generator, and a

supply of orifice and shielding gas. Accessory units such as an arc-voltage control and filler metal feed system may be used as required.

#### **4.2.2 Power Supply**

**4.2.2.1** Direct current power supplies with a drooping VA characteristic are used for plasma-arc welding. Rectifier-type units are preferred over motor generators for this service because rectifier output is less sensitive to variations in operating temperature. Also, automatic current sloping is simple with rectifiers. Rectifiers with an open circuit voltage in the range of 65 to 80 V (i.e., those used for gas tungsten-arc welding) are satisfactory for plasma-arc welding with argon or an argon-hydrogen gas mixture containing up to 7% hydrogen. However, if helium or an argon-hydrogen gas mixture containing more than 7% hydrogen is used, additional open circuit voltage is required for reliable arc ignition. This may be obtained by connecting two power supplies in series. An alternate approach requiring the use of only one power supply is to strike the arc in pure argon and then automatically switch over to the desired argon-hydrogen mixture or helium for the welding operation. Power supplies with current slope control are required for welding circumferential joints where the keyhole must be initiated and closed out gradually. Recent development work in plasma-arc welding aluminum and magnesium alloys indicates that the use of an alternating-current (a-c) power supply with a continuous high frequency arc can produce satisfactory welds.

#### **4.2.3 Control System**

**4.2.3.1** A typical control system for mechanized high current plasma-arc welding consists of a main console control, a junction box for gas and water hoses, a welding operator's pendant control box, and a high frequency generator.

**4.2.3.2** The main control unit sequences the power supply, high frequency generator, orifice, shielding and backing gases, torch travel, auxiliary wire feeding, and cooling water for the torch. Travel speed and wire feed rates are controlled by electronic governors.

**4.2.3.3** Flowmeters are provided for metering the orifice, shielding, and backing gases. In addition, timers and a gas-tapering device are provided for up- and down-sloping of the orifice gas flow. An adequate supply of cooling water for the torch electrode and constricting nozzle is provided by a pump with about 6 qt/min capacity. A flow switch and interlocking circuitry assure that cooling water is flowing to the torch before arc ignition can take place.

#### **4.2.4 Torches**

**4.2.4.1** Mechanized plasma-arc welding torches are available commercially for operation on either desp or derp (direct current reverse polarity) at currents up to 500 amperes. Straight polarity power is used with a tungsten electrode for most welding applications. Reverse polarity is used to a limited extent with water-cooled copper or tungsten electrodes for welding aluminum. Reverse polarity is also used with specially designed torches and copper electrodes for joining titanium and zirconium sponge compacts where freedom from tungsten or copper contamination is a prime consideration.

**4.2.4.2** A water-cooled power cable is used to bring power and cooling water into the torch; other hoses are provided for orifice-gas input, shielding-gas

input, and water return. The electrode holder in a plasma-arc welding torch is designed to center the electrode very accurately with respect to the central port in the nozzle. Misalignment of the electrode with the central port tends to cause melting of the copper nozzle near the orifice and to shorten its life.

**4.2.4.3** The relatively low orifice-gas flows used for welding do not provide adequate protection for the molten weld puddle. Accordingly, auxiliary shielding gas is supplied through an outer gas nozzle assembly on the torch. For some applications, additional trailing-gas shields may be required.

**4.2.4.4** A variety of nozzle designs exists for different welding applications. The diameter of the nozzle's orifice used in a particular application depends on the welding current to be used. Higher currents require larger diameter orifices.

#### **4.2.5 Wire Feeders**

**4.2.5.1** Conventional auxiliary wire feeding and hot-wire systems can be used with the plasma-arc welding process.

#### **4.2.6 Gases**

**4.2.6.1** See 5.4.

### **4.3 Powder Surfacing**

#### **4.3.1 General Requirements**

**4.3.1.1** All installations consist of a dual power supply, surfacing torch, control box, powder-dispenser unit, plumbing box, high-frequency generator, torch oscillator, cooling-water pump, and remote-control pendant.

#### **4.3.2 Power Supply**

**4.3.2.1** The dual power supply used for surfacing houses both the nontransferred and transferred arc power sources (see Fig. 9). Both sections have drooping VA characteristics similar to those used in gas tungsten-arc welding. The nontransferred arc section is connected between the tungsten electrode and the arc-constricting orifice. Its function is to maintain the 40-75 A nontransferred pilot arc used to initiate the main arc and, in some applications, to supplement the heat of the main transferred arc. The pilot arc is started by a high-frequency spark. The transferred arc power source is connected between the tungsten electrode and the workpiece to supply main arc currents between 20 and 500 amperes. Both power supplies are connected for dcsp operation.

#### **4.3.3 Control Unit**

**4.3.3.1** The control unit contains relays and timers for proper sequencing of electrical functions and electronic governors to control the powder-dispensing rate and carriage travel speed. Flowmeters are provided for metering orifice-, shielding-, and powder-dispensing gas flow rates, and a water-flow switch is provided for regulating the flow of cooling water to the torch. A remote pendant box is provided so the welding operator can control starting and stopping functions in close proximity to the work.

#### **4.3.4 Torches**

**4.3.4.1** The torch incorporates a standard tungsten electrode, an arc-constricting orifice, a means of directing gas-borne surfacing powders into the arc, a means of directing shielding gas around the weld puddle, and provisions for

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water cooling the constricting orifice and other critical areas. The arc-constricting orifice is larger than that used for welding and ranges between 1/8 in. and 3/16 in. in diameter. A heavy-duty nozzle assembly is available for some applications.

**4.3.5 Powder Feeders**

**4.3.5.1** Powders are stored and metered from a dispensing unit and transported to the surfacing torch in a stream of argon. Powder flow rates are adjusted by varying the speed of a rotating dispensing drum and the height of the dispensing nozzle above the drum.

**4.3.6 Gases**

**4.3.6.1** Argon is generally used for all three systems.

**4.4 Hot-Wire Surfacing****4.4.1 General Requirements**

**4.4.1.1** The surfacing system consists of a control panel assembly, plasma-arc power supply, hot-wire power supply, plasma-arc torch, two hot-wire guns with a trailing shield, an oscillator, and a voltage control head.

**4.4.2 Power Supply**

**4.4.2.1 Plasma-Arc Power Supply.** The plasma-arc power supply is a conventional direct current unit with provisions for remote current adjustment. Control of the plasma-arc current is provided by a "raise-lower" toggle switch on the pendant box.

**4.4.2.2 Hot-Wire Power Supply.** Power for the hot wires is provided by a special a-c constant potential supply. Its operating voltage is below the arc threshold which prevents an inadvertant sustained arc between the wires.

**4.4.3 Control Unit**

**4.4.3.1** The control cabinet for hot-wire surfacing with the plasma-arc welding process contains the preset control elements that generally do not need to be monitored during a surfacing operation. These controls include the preflow and postflow timers, the wire delay timers, the weld finish sequence timer, the flowmeters for the plasma-torch orifice and shielding-gas flow, the trailing shield-gas flow, and the crater-fill gas flow. The governor controls for the oscillator and wire feed motors, the arc voltage control, and an arc time meter are also mounted in the control cabinet. A high-frequency generator for starting the plasma arc, gas and water solenoids, meter shunts, and service connections are housed in a separate junction box. A pendant box is provided so the welding operator can position the welding head and start or stop the weld cycle from a remote location.

**4.4.4 Torches**

**4.4.4.1** The plasma-arc torch, hot-wire guns, oscillator, arc-voltage control head, and wire feeders are assembled as a self-contained unit which can be mounted on a boom or other type of fixturing.

**4.4.4.2** A single hot-wire feeding system may be used. The plasma-arc torch provides heat to fuse the deposit to the base metal. The hot-wire guns supply power for resistance heating of the filler metal and also serve as guides to direct the wires

into the puddle. Running adjustments are provided to control the position of the wires relative to the puddle.

**4.4.4.3** A trailing shield provides inert gas coverage for the weld puddle and serves as a mounting bracket for the hot-wire guns. The assembly is designed to permit removing the torches for servicing without disturbing wire adjustments.

**4.4.4.4** Cooling water is required for the plasma-arc welding torch, the hot-wire guns, and the trailing shield. The cooling water requirements are two gallons per minute at 100 psi. A recirculating cooling unit or any other suitable water supply may be used.

**4.4.4.5 Oscillator Assembly.** The oscillator assembly serves as a mount for the torch assembly and provides the transverse motion required for surfacing. The oscillation frequency is adjustable up to 80 cycles per minute, and the stroke is adjustable between 3/4 in. and 2 1/2 in.

**4.4.4.6 Arc-Voltage Control-Head Assembly.** This component is a rigid, motorized slide controlled by a servo-system to maintain constant plasma-arc voltage, hence constant torch-to-work distance. This system assures uniformity of deposit despite variations in vessel roundness, etc. Manual jogging of the slide provides motorized positioning of the torches in the vertical direction.

#### **4.4.5 Wire Feeders**

**4.4.5.1** The two wires are driven by a dual-wire feeder through standard wire feed accessories. Wire supply mountings accommodate either wire spools or coils. Two rotary, motor-driven straighteners are used to remove helix and cast from the wires. These wire straighteners are necessary to maintain a constant relationship in the wire entry into the weld puddle and assure uniformity of deposit over long operating cycles.

#### **4.4.6 Gases**

**4.4.6.1** Three separate gas flows are used for hot-wire surfacing with the plasma-arc welding process. A 55 cfh flow of a 75% helium-25% argon mixture passes through the plasma-arc torch orifice to support the transferred arc. Thirty to sixty cfh of argon passes through the torch shield to protect the arc zone. Another flow of 30 to 60 cfh of argon is used in the trailing shield assembly to protect the surfacing deposits.

## **5. Application of the Plasma-Arc Welding Process to Metal Joining**

### **5.1 General Areas of Application**

**5.1.1** The plasma-arc welding process is applicable to metals weldable by the gas tungsten-arc welding process.

**5.1.2** For plate thicknesses in the 1/4 in. range, square-groove welds are made in butt joints without filler metal addition at up to twice the travel speed of the gas tungsten-arc welding process, with the keyhole mode of the plasma-arc welding process. Table 1 illustrates the welding speeds typical on stainless steel tubing. At thicknesses from 1/16 in. down to 0.002 in., the low-current nonkeyhole mode of

**Table 1 — Typical plasma-arc welding speeds for welding stainless steel tubing**

| <u>Wall Thickness (in.)</u> | <u>Plasma-Arc Welding Speed (ipm)</u> |
|-----------------------------|---------------------------------------|
| 0.109                       | 36                                    |
| 0.125                       | 36                                    |
| 0.154                       | 36                                    |
| 0.216                       | 15                                    |
| 0.237                       | 14                                    |

the plasma-arc welding process is applicable. Speed is no longer an advantage for these thicknesses but the other advantages associated with the process remain.

## 5.2 Base Metals

**5.2.1** The plasma-arc welding process is applicable to the wide range of metals considered weldable by other processes. The fully-killed carbon and low-alloy steels, including AISI 4130 and 2 1/4 Cr-1 Mo, are readily joined as are most austenitic, martensitic, and ferritic stainless steels. The weldable aerospace superalloys in the Hastelloy\* series and Inconel\*\* 718, special application steel alloys such as D6AC, the 9 Ni-4Co series, the 18% Ni maraging group, and titanium and its weldable alloys such as 6 Al-4V are also weldable by the plasma-arc welding process.

The metallurgical effects the process has on metals are not different from other processes, and appropriate procedures that preserve metallurgical integrity must be followed. Preheat, postheat, shielding, and gas selection are similar to those used with the gas tungsten-arc welding process. Metals joined may determine the gas mixtures used, particularly in the case of hydrogen additions to orifice and shielding gas, where the quality of the welds in titanium and low-alloy steels would be severely degraded. (The tables under 5.12.3 list welding conditions for a variety of metals.) There is limited information on the application of the plasma-arc welding process to aluminum and magnesium alloys. Some success has been achieved in producing satisfactory welds by special system setups using an a-c power supply and continuous high frequency superimposed upon the arc.

## 5.3 Filler Metal Addition

**5.3.1** For nonkeyhole mode welding, filler metal can be added to the leading edge of a plasma-arc weld puddle in the same manner as with the gas tungsten-arc welding process. Hot-wire systems feed wire into the trailing edge of the weld puddle for filler passes. Wire height adjustments are not so critical with plasma-arc welding because the wire can be lifted off the plate and melted into the plasma stream without contaminating the electrode.

\*Trademark of Stellite Division, Cabot Corporation.

\*\*Trademark of International Nickel Company.

**5.3.2** For the keyholing method, filler metal can be added to the leading edge of the puddle formed by the keyhole. The molten weld metal will flow around the keyhole to form a reinforced weld bead. Depending on fitup and bead contour requirements, this technique may be used on single pass welds in butt joints with a square-groove joint preparation in metals up to about 1/4 in. thick. On heavier sections, a joint preparation is selected that will allow the plasma jet to melt the maximum amount of base metal supportable by surface tension. For this reason, filler metal is generally not added in making the root pass of a multipass weld.

**5.3.3** Keyhole-mode circumferential welds in butt joints with square-groove joint preparation require close control of timing and slope rates for arc current and orifice-gas flow during keyhole initiation and withdrawal. The addition of filler metal in making such welds may complicate the keyhole withdrawal operation and may be undesirable for such applications.

**5.3.4** The type of filler metal used is determined by the metallurgical factors involved and is based on recommendations and uses developed for other processes.

## 5.4 Gases

**5.4.1** Argon is the preferred orifice gas for low-current plasma-arc welding because its low ionization potential assures reliable starting and a dependable pilot arc. Since the pilot arc is used only to maintain ionization in the plenum chamber, pilot arc current is not critical and can be fixed for a wide variety of operating conditions. In commercial units, the recommended orifice-gas flow rates are less than 1 cfh, and the pilot arc current is fixed at five amperes.

**5.4.2** The shielding gas provided through the gas nozzle can be argon, an argon-hydrogen mixture, or an argon-helium mixture, depending on the welding application. Shielding gas flow rates are usually in the range of 20 to 30 cfh for low current applications.

**5.4.3** Various percentages of argon-hydrogen mixtures can be obtained by blending argon and cylinder premixes of 5% hydrogen in argon (H-5) or 15% hydrogen in argon (H-15). The required ratios can be obtained by using the flowmeter settings shown in Table 2.

**5.4.4** The choice of gas to be used for plasma-arc welding depends on the metal to be welded. In all but a few cases, the shielding gas is the same as the orifice gas because variations in the consistency of the arc effluent would be inevitable if two different types of gas were used. Although argon is suitable as the orifice and shielding gas for welding all metals, it does not necessarily produce optimum welding results. As in gas tungsten-arc welding, additions of hydrogen to argon produce a hotter arc and efficient heat transfer to the workpiece. In this way, higher welding speeds are obtained with a given arc current. The amount of hydrogen that can be used in the mixture is limited because excessive hydrogen additions tend to cause porosity or cracking in the weld bead. With the plasma-arc keyhole technique, a given metal thickness can be welded with higher percentages of hydrogen than are possible in the gas tungsten-arc welding process. The ability to use higher percentages of hydrogen without inducing porosity may be associated with the keyhole effect and the different solidification pattern it produces.

**Table 2 — Flowmeter settings for argon-hydrogen shielding gas mixtures**

| Flowmeter Settings (1) |                            | Percentage of Hydrogen (2) |                 |
|------------------------|----------------------------|----------------------------|-----------------|
| Scale<br>Argon<br>cfh  | Scale<br>(Ar-H) Mix<br>cfh | For<br>H-5 Mix             | For<br>H-15 Mix |
| 20                     | 0                          | 0                          | 0               |
| 16                     | 4                          | 1                          | 3               |
| 12                     | 8                          | 2                          | 6               |
| 10                     | 10                         | 2 1/2                      | 7 1/2           |
| 8                      | 12                         | 3                          | 9               |
| 4                      | 16                         | 4                          | 12              |
| 0                      | 20                         | 5                          | 15              |

Note: (1) 20 cfh total shielding gas flow.

(2) Percentage of hydrogen based on blending with premix of H-5 or H-15.

**5.4.5** Argon is used for welding carbon steel, high-strength steels, and reactive metals such as titanium and zirconium alloys. Even minute quantities of hydrogen in the gas used to weld these metals may result in porosity, cracking, or reduced mechanical properties.

**5.4.6** Argon-hydrogen mixtures are used as the orifice and shielding gases for making keyhole-mode welds in stainless steel, nickel-base, and copper-nickel alloys.

**5.4.7** Permissible hydrogen percentages vary from the 5% used on 1/4 in. thick stainless steel to the 15% used for highest welding speeds on 0.150 in. and thinner wall stainless tubing in tube mills. In general, the thinner the workpiece, the higher the permissible percentage of hydrogen in the gas mixture up to a maximum of 15 percent.

**5.4.8** Use of helium as an orifice gas increases the heat load on the torch nozzle and reduces its service life and current capacity. Because of the lower mass of helium, it is difficult, at reasonable flow rates, to obtain a keyhole condition with this gas. Therefore, helium is used only for making nonkeyhole-mode welds.

**5.4.9** Helium additions to argon produce a hotter arc for a given arc current. A mixture must contain at least 50% helium before a significant change can be detected; mixtures containing over 75% helium behave about the same as pure helium. Argon-helium mixtures containing between 50 and 75% helium are generally used for making keyhole-mode welds in heavier titanium sections and for filler passes on all metals when the additional heat and wider heat pattern obtained from these mixtures are desirable.

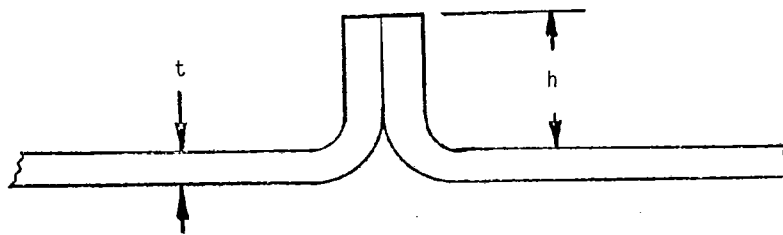
## **5.5 Auxiliary Weld Shielding**

**5.5.1** It is useful to supply auxiliary weld shielding in welding titanium and other metals that react with air and may suffer degradation of metallurgical

properties as a result. In addition, air can substantially alter the fluidity of the molten weld metal in several base metals. This can change the keyholing characteristics. For such applications an auxiliary shield is beneficial in reducing variations in weldability. This auxiliary shielding is also necessary when welding more common and less reactive metals at high travel speeds. An important part of the auxiliary shield is the insulator between the torch and the shield; pyrex glass provides excellent electrical insulation and the temperature stability and stiffness necessary to transfer dragging forces from the torch to the shield.

## 5.6 Joint Design

**5.6.1** In metal thicknesses of 0.002 to 0.010 in., edge-flange welds can be made with the plasma-arc welding process in the nonkeyhole-mode operation. Flanging of the panel edges can be accomplished with a rolling flanger. Typical flange heights are shown in Fig. 11.

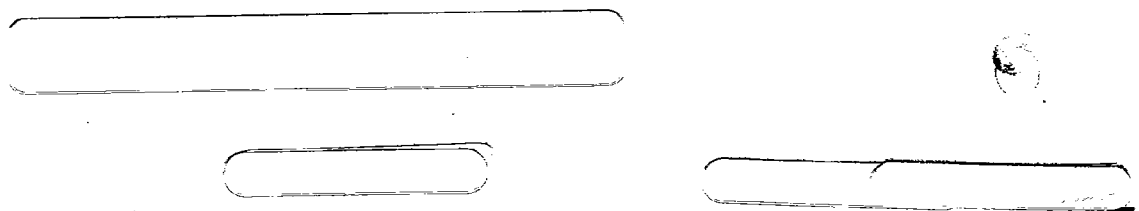


| Metal thickness, $t$ (in.) | Flange height, $h$ (in.) |
|----------------------------|--------------------------|
| 0.002                      | 0.010 to 0.020           |
| 0.005                      | 0.020 to 0.025           |
| 0.010                      | 0.030 to 0.040           |

Fig. 11 - Flange heights for edge-flange welds.

**5.6.2** In 0.010 to 0.060 in. thick metal sections, butt joints with square-groove design are commonly used for plasma-arc welding. In this thickness range, the nonkeyhole mode of plasma-arc welding is used. Tee, edge, and corner joints are easily welded with or without filler metal addition.

**5.6.3** Metal thicknesses of 0.060 to 1/4 in. are usually welded with square-groove welds in butt joints utilizing the keyhole mode of the plasma-arc welding process. These welds are made in one pass, usually without filler metal addition. The sides of the fusion zone are more parallel and narrower than those made with the gas tungsten-arc welding process. This results in reduced joint shrinkage and distortion. Joint gap and mismatch are not so critical as in gas tungsten-arc welding because of the stiffness of the plasma-arc stream and its insensitivity to variations in voltage. Tee and edge joints can be welded in this



range of thicknesses using nonkeyhole-mode operation. Fillet welds, with filler metal addition, tend to be deeply penetrated with a concave fillet surface.

**5.6.4** Metal thicknesses over 1/4 to 1 in. require a U or Vee preparation for butt welding. However, a simple square-groove weld can be made in metal thicknesses up to 5/8 in. when welding from both sides. Beyond 5/8 in., U- or Vee-type grooves—single or double—must be used. These groove configurations can incorporate substantially wider root faces (up to 1/4 in.) than those used in gas tungsten-arc welding (see Fig. 12). In this way, plate thicknesses approaching 1 in. can be welded with the root pass made in the keyhole mode and subsequent filler passes in the nonkeyhole mode.

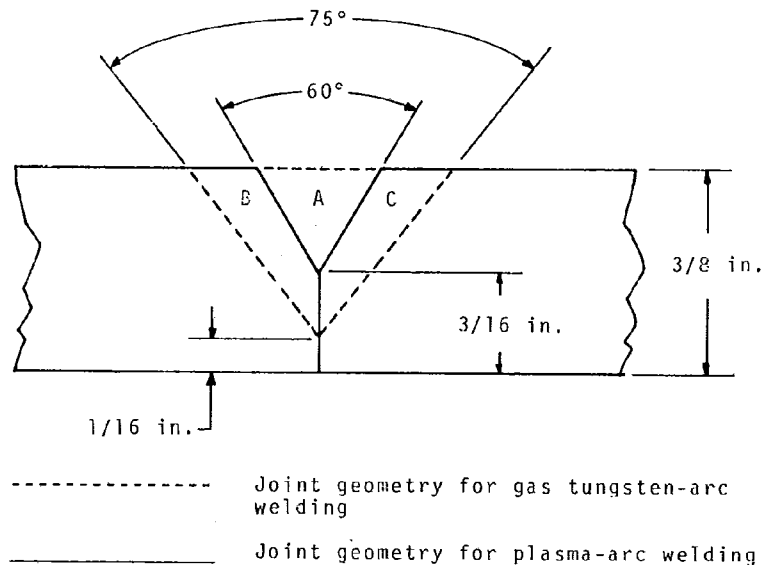
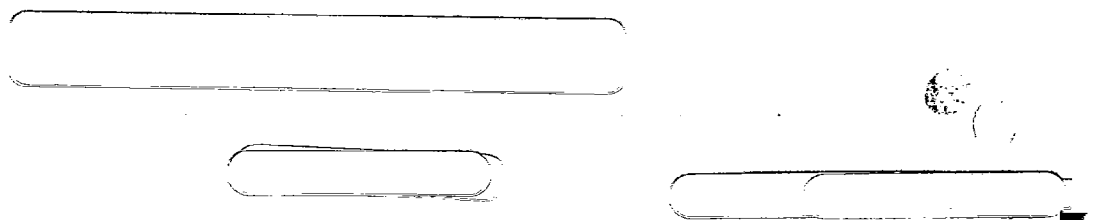


Fig. 12 – Comparison of typical joint geometries for gas tungsten-arc and plasma-arc welds on 3/8 in. thick steel.

**5.6.5** The common types of welds successfully made with the plasma-arc welding process are: square-groove, single- and double-U-groove, and single- and double-Vee-groove. These are generally used for welding butt joints from one or both sides of the joint and with single- or multiple-pass welding. Fillet welds can be made using a technique similar to gas tungsten-arc welding. Tee joints can be welded with the plasma arc by penetrating the web member from the flange-member side of the tee, thus simultaneously producing a fillet on both sides of the web member. The fillet is generated from the portion of the web members that protrudes through the abutting flange-member components. metal may also be added to the weld puddle to provide the fillet.

## 5.7 Tooling Practices

**5.7.1** In general, tooling requirements for plasma-arc welding are simpler and therefore less expensive than for gas tungsten-arc or gas metal-arc welding. The keyholing technique essentially equalizes contraction stresses at the top and



bottom of the weld. Therefore, tooling has a smaller distortion tendency to counteract, and can be simpler when using the keyhole mode.

**5.7.2** Keyholing eliminates the need for an underbead heat sink such as a copper backup bar. Instead, a gap is necessary for accommodating the joint-penetrating plasma. In this mode of operation, a backing bar with a simple rectangular groove (as shown in Fig. 13) is sufficient. Because the weld puddle is supported by the surface tension of the molten metal and does not contact the backing bar, underbead gas shielding is always required to protect the molten underbead from atmospheric contamination. Hence, the use of such a backing bar serves to support the weldment, to contain the underbead shielding gas, and to provide a vent space for the plasma jet. Groove dimensions are generally about 1/2 in. wide and 3/4 in. deep. Argon or helium can be used as the underbead shielding gas. In some applications where the purge volume is in the form of a relatively closed chamber, it is important to use helium as the underbead shielding gas.

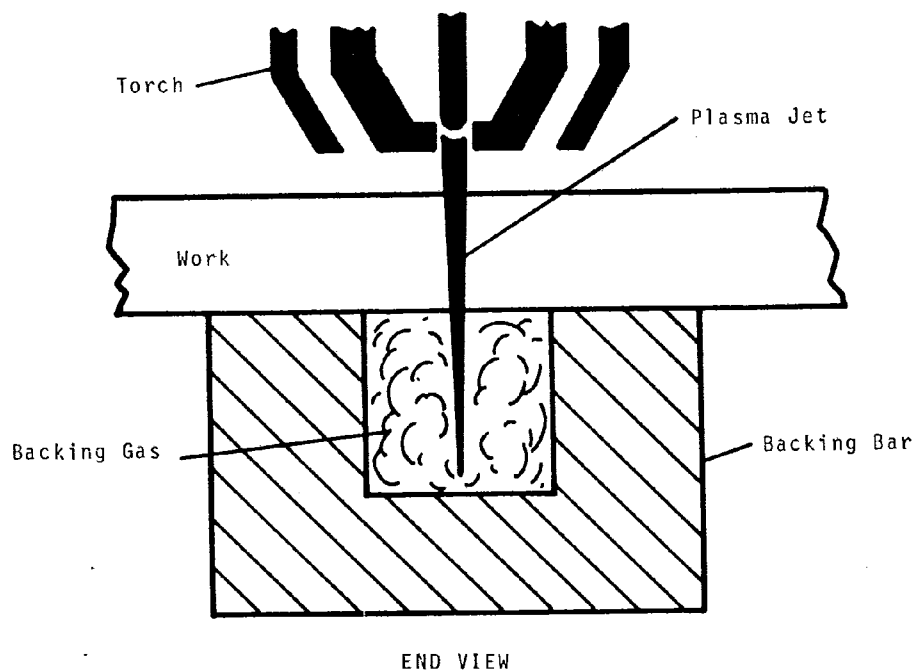


Fig. 13 – Typical backing bar for plasma-arc welding.

**5.7.3** Where a trailing shield is necessary, shield length must be much longer — 50 to 100% — than for gas tungsten-arc welding because welding speeds are considerably faster for plasma-arc welding. The faster travel speed also diminishes the tolerance for filler metal inlet or trailing shield attachment openings at the torch. Such openings more easily scoop in air that contaminates (embrittles) the weld bead or discolors (oxidizes) the weld surface.

**5.7.4** The high plasma velocity due to plasma-arc constriction makes the arc much more resistant to deflection than the gas tungsten-arc. Therefore, the arc is quite stable in the vicinity of sharp or protruding edges such as joint mismatch, and can more readily accommodate them than the gas tungsten-arc. This is another reason why tooling may be simpler and more economical.

## **5.8 Manual Welding**

**5.8.1** Manual plasma-arc welding is generally limited to applications up to 100 A with apparatus designed to be hand-held, and where contour welding is necessary. The recently developed apparatus uses a pilot-arc system and a foot contactor to transfer welding current through the plasma stream. The pilot plasma arc visible to the welder wearing protective lens, facilitates accurate positioning of the torch for weld starting. Transfer to weld current is positive and instantaneous, not subject to the difficulties inherent in the gas tungsten-arc welding process, starting at low welding currents.

**5.8.2** The pilot arc is started by moving the electrode forward until it touches the nozzle and then retracting it. The pilot-arc circuit is always energized when the unit is in use. The transferred-arc circuit is then energized by closing a contactor in the lead to the workpiece. Another system utilizes high frequency to start the pilot arc, and a single power supply.

**5.8.3** Like manual gas tungsten-arc welding, manual plasma-arc welding is better adapted to nonkeyhole, fusion-type welding. Higher-current (approximately 100 A and above) plasma-arc welding is usually mechanized to obtain the benefits of the keyhole technique; low-current plasma-arc welding can be performed manually as well as with mechanization. Manual plasma-arc welding can be used in all positions common to gas tungsten-arc welding.

## **5.9. Mechanized Welding**

**5.9.1** Mechanized welding is required for high-current plasma-arc applications such as making keyhole-mode welds or high-current filler passes. Mechanization is required because of the high travel speeds, the need for accurate joint alignment, narrow plasma-arc weld fusion zones, and the types of apparatus available. For repetitive operations, mechanized welding is applicable, as it would be for other processes. Mechanized welding is applied to low-current applications where advantageous.

**5.9.2** The mechanized plasma-arc torch utilizes high frequency to initiate a pilot arc between the electrode and the constricting nozzle. The ionized gas generated by the low-current pilot arc flows through the constricting orifice, to the workpiece and completes the circuit for the main welding arc. In most systems, the high-frequency generator and pilot arc are turned off after the main arc is initiated.

**5.9.3** The high-current mechanized plasma-arc welding system is capable of utilizing the keyhole mode in approximate thicknesses of 1/16 to 1/4 in. Recent tests indicate that, when joining titanium alloys, straight butt joints can be welded with the keyhole technique up to 1/2 in. thick. Low-current, mechanized, plasma-arc welding can utilize the keyhole mode down to an approximate thickness of 1/32 in. Application to thicknesses above 1/4 in. in a butt joint may

require joint preparation, but can use a root face up to 1/4 in. wide. Addition of filler metal to fill the prepared joint using multiple-pass welding procedures is commonly done in plasma-arc welding. The practical limit of application is approximately a 1 in. thick Vee groove, where the plasma-torch nozzle size prevents accessibility to the root of the joint. Further development is necessary in and above this thickness range.

**5.9.4** When welding metal thicknesses under 1/8 in., keyhole-mode welds for straight seam and circumferential welding can be started at full operating current, travel speed, and orifice-gas flow. In this thickness range, the keyhole is developed with little disturbance in the weld puddle, and the weld surface and underbead are reasonably smooth.

**5.9.5** It is important to differentiate between straight seam welds, where runoff tabs can be utilized to isolate the keyhole initiation and withdrawal areas, and circumferential or girth type welds where the keyhole initiation and withdrawal zones must be included within the inspectable weld fusion zone. The operating currents and orifice gas velocity required for keyhole-mode welds in thicknesses greater than approximately 1/8 in. generally produce a plasma stream that tends to gouge or tunnel underneath molten metal during keyhole initiation. Because the gouging action may cause plasma gas-entrapment voids and severe surface irregularities, runoff tabs are usually used to make straight seam welds in the keyhole mode in these thicknesses. When welding circumferential joints, runoff tabs cannot be used; a suitable keyhole initiation zone can be achieved using a programmed increase in welding current and orifice-gas flow rate with travel speed set at the welding rate. Any gas entrapment voids that may form in the keyhole initiation area are removed by the overlapping keyhole and are not generally a quality problem. These important sloping functions for welding current and orifice-gas flow rate are normally produced automatically by commercial welding equipment and controls. See 5.12, Figs. 14, 16, 17 and 20.

**5.9.6** If the keyholing plasma arc is abruptly interrupted at the end of a circumferential weld, a variety of weld defects may occur. Although abrupt keyhole termination may be desirable in straight seam welds, it is necessary to employ a very different keyhole termination procedure for circumferential welds in the various metals and thicknesses. The principal problem area in keyhole-mode circumferential welds is the keyhole withdrawal zone.

**5.9.7** Proper termination of the keyhole in a circumferential weld requires down-sloping the arc current and orifice-gas flow rate. The net effect of this procedure is to gradually reduce the keyholing force of the plasma arc while retaining the arc heat necessary to maintain puddle fluidity as the keyhole is filling in. Travel speed is generally maintained at the welding rate. Specific metals generally require variations in down-slope time phasing and duration using this procedure, and in some cases it may be beneficial to simultaneously reduce the travel speed to help in maintaining puddle fluidity during the time the keyhole is being filled. See 5.12, Figs. 14, 16, 17 and 20.

**5.9.8** Mechanized plasma-arc welding is usually performed in the flat position. Limited work in horizontal and vertical welding has been satisfactorily accomplished.

Table 3 — Typical plasma-arc welding conditions for welding butt joints in stainless steel

| Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Arc<br>Voltage<br>(V) | Nozzle<br>Type <sup>a</sup> | Orifice <sup>c</sup><br>(cfh) | Gas Flow <sup>b</sup><br>Shield <sup>d</sup><br>(cfh) | Remarks                                                                     |
|--------------------|--------------------------|------------------------|-----------------------|-----------------------------|-------------------------------|-------------------------------------------------------|-----------------------------------------------------------------------------|
| 0.092              | 24                       | 115                    | 30                    | 111M                        | 6                             | 35                                                    | Keyhole, square-groove<br>weld                                              |
| 0.125              | 30                       | 145                    | 32                    | 111M                        | 10                            | 35                                                    | Keyhole, square-groove<br>weld                                              |
| 0.187              | 16                       | 165                    | 36                    | 136M                        | 13                            | 45                                                    | Keyhole, square-groove<br>weld                                              |
| 0.250              | 14                       | 240                    | 38                    | 136M                        | 18                            | 50                                                    | Keyhole, square-groove<br>weld                                              |
| 0.375              | Root<br>Pass             | 230                    | 36                    | 136M                        | 12                            | 45                                                    | Keyhole, Vee-groove<br>with 3/16 in. root face<br>and 60 deg included angle |
|                    | Filler<br>Pass           | 220                    | 40                    | 136M <sup>e</sup>           | 25                            | 175 <sup>e</sup>                                      | 60 ipm of 0.045 in.<br>wire as filler metal                                 |

<sup>a</sup>Nozzle type - Number designates orifice diam in thousandths of an inch; "M" designates multipoint design.

<sup>b</sup>Gas underbead shielding required for all welds.

<sup>c</sup>Gas used - 95% Ar, 5% H.

<sup>d</sup>Torch standoff - 3/16 in.

<sup>e</sup>Gas used - helium.

Table 4 — Typical plasma-arc welding conditions for welding butt joints in carbon and low-alloy steels

| Metal      | Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Arc<br>Voltage<br>(V) | Nozzle<br>Type <sup>a</sup> | Gas Flow <sup>b</sup><br>Orifice <sup>c</sup><br>(cfh) | Shield <sup>d</sup><br>(cfh) | Remarks                                                                         |
|------------|--------------------|--------------------------|------------------------|-----------------------|-----------------------------|--------------------------------------------------------|------------------------------|---------------------------------------------------------------------------------|
| Mild Steel | 0.125              | 12                       | 185                    | 28                    | 111M                        | 13                                                     | 60                           | Keyhole, square-groove weld                                                     |
| 4130 Steel | 0.170              | 10                       | 200                    | 29                    | 136M                        | 12                                                     | 60                           | Keyhole, square-groove weld, 30 ipm of 3/64 in. diam wire added as filler metal |
| 06ac Steel | 0.250              | 14                       | 275                    | 33                    | 136M                        | 15                                                     | 60                           | Keyhole, square-groove weld, 600 F preheat, 750 F postheat for one hour         |

<sup>a</sup>Nozzle type - Number designates orifice diam in thousandths of an inch; "M" designates multipoint design.

<sup>b</sup>Gas underbead shielding required for all welds.

<sup>c</sup>Gas used - Argon.

<sup>d</sup>Torch standoff - 3/64 in. for all welds.

Table 5 — Typical plasma-arc welding conditions for welding butt joints in titanium

| Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Arc<br>Voltage<br>(V) | Nozzle<br>Type <sup>a</sup> | Gas Flow <sup>b</sup><br>Orifice<br>(cfh) | Shield<br>(cfh) | Remarks <sup>c</sup>                                    |
|--------------------|--------------------------|------------------------|-----------------------|-----------------------------|-------------------------------------------|-----------------|---------------------------------------------------------|
| 0.125              | 20                       | 185                    | 21                    | 111M                        | 8 <sup>d</sup>                            | 60 <sup>d</sup> | Keyhole, square-groove<br>weld                          |
| 0.187              | 13                       | 175                    | 25                    | 136M                        | 18 <sup>d</sup>                           | 60 <sup>d</sup> | Keyhole, square-groove<br>weld                          |
| 0.390              | 10                       | 225                    | 38                    | 136M                        | 32 <sup>e</sup>                           | 60 <sup>e</sup> | Keyhole, square-groove<br>weld                          |
| 0.500              | 10                       | 270                    | 36                    | 136M                        | 27 <sup>f</sup>                           | 60 <sup>f</sup> | Keyhole, square-groove<br>weld                          |
| 0.600              | 7                        | 250                    | 39                    | 136M                        | 30 <sup>f</sup>                           | 60 <sup>f</sup> | Keyhole, 3/8 in. root<br>face, 30 deg included<br>angle |

<sup>a</sup>Nozzle type - Number designates orifice diam in thousandths of an inch; "M" designates multiport design.

<sup>b</sup>Gas underbead shielding required for all welds.

<sup>c</sup>Torch standoff - 3/16 in.

<sup>d</sup>Gas used - argon.

<sup>e</sup>Gas used - 75% He, 25% Ar.

<sup>f</sup>Gas used - 50% He, 50% Ar.

Table 6 — Typical plasma-arc welding conditions for welding butt joints in copper and brass

| Metal                  | Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Arc<br>Voltage<br>(V) | Nozzle<br>Type <sup>a</sup> | Gas Flow <sup>b,c</sup><br>Orifice<br>(cfh) | Remarks <sup>d,e</sup>          |
|------------------------|--------------------|--------------------------|------------------------|-----------------------|-----------------------------|---------------------------------------------|---------------------------------|
| Copper                 | 0.094              | 10                       | 180                    | 28                    | 111M                        | 10 <sup>f</sup>                             | Keyhole                         |
| Copper                 | 0.125              | 10                       | 300                    | 33                    | 136M                        | 89                                          | Nonkeyhole, graphite<br>backing |
| Copper <sup>h</sup>    | 0.250              | 20                       | 670                    | 46                    | 375                         | 59                                          | Nonkeyhole, graphite<br>backing |
| Brass<br>(70 Cu-30 Zn) | 0.080              | 20                       | 140                    | 25                    | 111M                        | 8 <sup>f</sup>                              | Keyhole                         |
| Brass<br>(70 Cu-30 Zn) | 0.125              | 16                       | 200                    | 27                    | 136M                        | 10 <sup>f</sup>                             | Keyhole                         |

<sup>a</sup>Nozzle type - Number designates orifice diam in thousandths of an inch; "M" designates multiport design.

<sup>b</sup>Gas underbead shielding required.

<sup>c</sup>Shielding gas - 60 cfh, argon for all welds.

<sup>d</sup>Torch standoff - 3/16 in.

<sup>e</sup>All welds are square-groove welds in butt joints.

<sup>f</sup>Gas used - Argon.

<sup>g</sup>Gas used - Helium.

<sup>h</sup>Strip mill splicing application.

Table 7 — Typical plasma-arc welding conditions for welding butt joints in nickel and nickel base alloys

| Metal                         | Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Arc<br>Voltage<br>(V) | Nozzle<br>Type <sup>a</sup> | Gas Flow <sup>b,c</sup><br>Orifice<br>(cfh) | Remarks <sup>d,e</sup>      |
|-------------------------------|--------------------|--------------------------|------------------------|-----------------------|-----------------------------|---------------------------------------------|-----------------------------|
|                               |                    |                          |                        |                       |                             |                                             |                             |
| Nickel                        | 0.125              | 27                       | 200                    | 30                    | 111M                        | 15 <sup>i</sup>                             | Keyhole, square-groove weld |
| Nickel                        | 0.250              | 14                       | 250                    | 30                    | 136M                        | 10 <sup>i</sup>                             | Keyhole, square-groove weld |
| Haynes Alloy #25 <sup>f</sup> | 0.109              | 36                       | 165                    | 31 1/2                | 111M                        | 10 <sup>j</sup>                             | Keyhole, square-groove weld |
| Haynes Alloy #25 <sup>f</sup> | 0.109              | 24                       | 185                    | 28 1/2                | 111M                        | 10 <sup>k</sup>                             | Keyhole, square-groove weld |
| Hastelloy C                   | 0.109              | 18                       | 150                    | 25                    | 111M                        | 8 <sup>k</sup>                              | Keyhole, square-groove weld |
| Incoloy 800 <sup>g</sup>      | 0.125              | 27                       | 180                    | 31                    | 111M                        | 15 <sup>i</sup>                             | Keyhole, square-groove weld |
| Incoloy 800 <sup>g</sup>      | 0.250              | 14                       | 230                    | 30                    | 136M                        | 12 1/2 <sup>i</sup>                         | Keyhole, square-groove weld |
| Inconel X                     | 0.125              | 27                       | 180                    | 13                    | 111M                        | 15 <sup>i</sup>                             | Keyhole, square-groove weld |
| Inconel X                     | 0.250              | 14                       | 230                    | 30                    | 136M                        | 12 1/2 <sup>i</sup>                         | Keyhole, square-groove weld |
| Inconel 600                   | 0.140              | 30                       | 185                    | 30                    | 111M                        | 13 <sup>j</sup>                             | Keyhole, square-groove weld |
| Rene 41 <sup>h</sup>          | 0.050              | 8.5                      | 50                     | --                    | 111M                        | 2.5 <sup>k</sup>                            | Keyhole, square-groove weld |
| Rene 41 <sup>h</sup>          | 0.125              | 7.5                      | 100                    | --                    | 111M                        | 15 <sup>k</sup>                             | Keyhole, square-groove weld |
| 18% Nickel<br>Maraging Steel  | 0.250              | 13.5                     | 225                    | 29                    | 136M                        | 13 <sup>k</sup>                             | Keyhole, square-groove weld |

Table 7 (continued) — Typical plasma-arc welding conditions for welding butt joints in nickel and nickel base alloys

| Metal                        | Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>— dcs —<br>(A) | Arc<br>Voltage<br>(V) | Nozzle<br>Type <sup>a</sup> | Gas Flow <sup>b,c</sup> |         | Remarks <sup>d,e</sup>                                                      |
|------------------------------|--------------------|--------------------------|---------------------------|-----------------------|-----------------------------|-------------------------|---------|-----------------------------------------------------------------------------|
|                              |                    |                          |                           |                       |                             | Gas                     | Orifice |                                                                             |
| 18% Nickel<br>Maraging Steel | 0.313              | Root<br>Pass             | 250                       | --                    | 136M                        | 11 <sup>k</sup>         |         | Keyhole, Vee-groove with<br>3/16 in. root face and<br>60 deg included angle |
|                              |                    | Filler<br>Pass           | 250                       | --                    | 136M                        | 4 <sup>l</sup>          |         | Nonkeyhole, 3/32 in.<br>diam wire added at<br>32 ipm as filler metal        |

<sup>a</sup>Nozzle type - Number designates orifice diameter in thousandths of an inch; "M" designates multipoint design.

<sup>b</sup>Gas underbead shielding required for all welds.

<sup>c</sup>Shielding gas - 60 cfh minimum for all welds.

<sup>d</sup>Electrode setback should be maintained at 1/8 in. for all welds.

<sup>e</sup>Torch standoff: (1) For square-groove welds: 3/16 in. from plate surface.  
(2) For other groove welds: 1/8 in. from plate surface.

<sup>f</sup>Trademark of Stellite Div., Cabot Corp.

<sup>g</sup>Trademark of the International Nickel Co.

<sup>h</sup>Trademark of General Electric Co.

<sup>i</sup>Gas used - 95% Ar, 5% H.

<sup>j</sup>Gas used - 92.5% Ar, 7.5% H.

<sup>k</sup>Gas used - Argon.

<sup>l</sup>Gas used - 75% Ar, 25% He.

**Table 8 — Typical plasma-arc welding conditions for welding butt joints in thin gage metals**

| Metal           | Thickness<br>(in.) | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Gas <sup>a,b</sup><br>Shielding | Remarks <sup>c</sup> |
|-----------------|--------------------|--------------------------|------------------------|---------------------------------|----------------------|
| Stainless Steel | 0.001              | 5                        | 0.3                    | 99% Ar+1% H                     | Edge-flange weld     |
| "               | 0.003              | 6                        | 1.6                    | 99% Ar+1% H                     | Edge-flange weld     |
| "               | 0.006              | 5                        | 2.0                    | 99% Ar+1% H                     |                      |
| "               | 0.010              | 8                        | 6.0                    | 99% Ar+1% H                     |                      |
| "               | 0.030              | 5                        | 10.0                   | 99% Ar+1% H                     |                      |
| Titanium        | 0.003              | 6                        | 3.0                    | 50% Ar+50% He                   | Edge-flange weld     |
| "               | 0.008              | 5                        | 5.0                    | Ar                              |                      |
| "               | 0.015              | 5                        | 5.8                    | Ar                              |                      |
| "               | 0.022              | 7                        | 10.0                   | 85% He+25% Ar                   |                      |
| Inconel 718     | 0.012              | 15                       | 6.0                    | 75% He+25% Ar                   |                      |
| Hastelloy X     | 0.005              | 10                       | 4.8                    | Ar                              |                      |
| "               | 0.010              | 8                        | 5.8                    | Ar                              |                      |
| "               | 0.020              | 10                       | 10.0                   | Ar                              |                      |
| Copper          | 0.003              | 6                        | 10.0                   | 75% He+25% Ar                   | Edge-flange weld     |

<sup>a</sup>Orifice gas - 0.5 cfh argon for all welds.<sup>b</sup>Shielding gas flow rate - 20 cfh - total.<sup>c</sup>Orifice diam - 0.030 in.

**Table 9 — Typical plasma-arc welding conditions for welding edge joints  
in thin gage metals**

| <u>Metal</u>       | <u>Thickness</u><br>(in.) | <u>Travel</u><br><u>Speed</u><br>(ipm) | <u>Current</u><br><u>dcsp</u><br>(A) | <u>Gas<sup>a,b,c</sup></u><br><u>Shielding</u> |
|--------------------|---------------------------|----------------------------------------|--------------------------------------|------------------------------------------------|
| Stainless Steel    | 0.001                     | 5                                      | 0.3                                  | 99% Ar+1% H                                    |
| " "                | 0.005                     | 15                                     | 1.6                                  | 99% Ar+1% H                                    |
| " "                | 0.010                     | 5                                      | 4.0                                  | 99% Ar+1% H                                    |
| Titanium           | 0.003                     | 5                                      | 1.6                                  | Ar                                             |
| "                  | 0.008                     | 5                                      | 3.0                                  | Ar                                             |
| Hastelloy X        | 0.005                     | 10                                     | 1.5                                  | 99% Ar+1% H                                    |
| " "                | 0.010                     | 3                                      | 3.0                                  | Ar                                             |
| " "                | 0.020                     | 7                                      | 6.5                                  | Ar                                             |
| Kovar <sup>d</sup> | 0.011                     | 20                                     | 9.0                                  | 95% Ar+5% H                                    |

<sup>a</sup>Orifice gas - 0.5 cfh argon for all welds.

<sup>b</sup>Shielding gas flow rate - 20 cfh - total.

<sup>c</sup>Orifice diam - 0.030 in.

<sup>d</sup>Trademark of Stupakoff Ceramic & Mfg. Co.

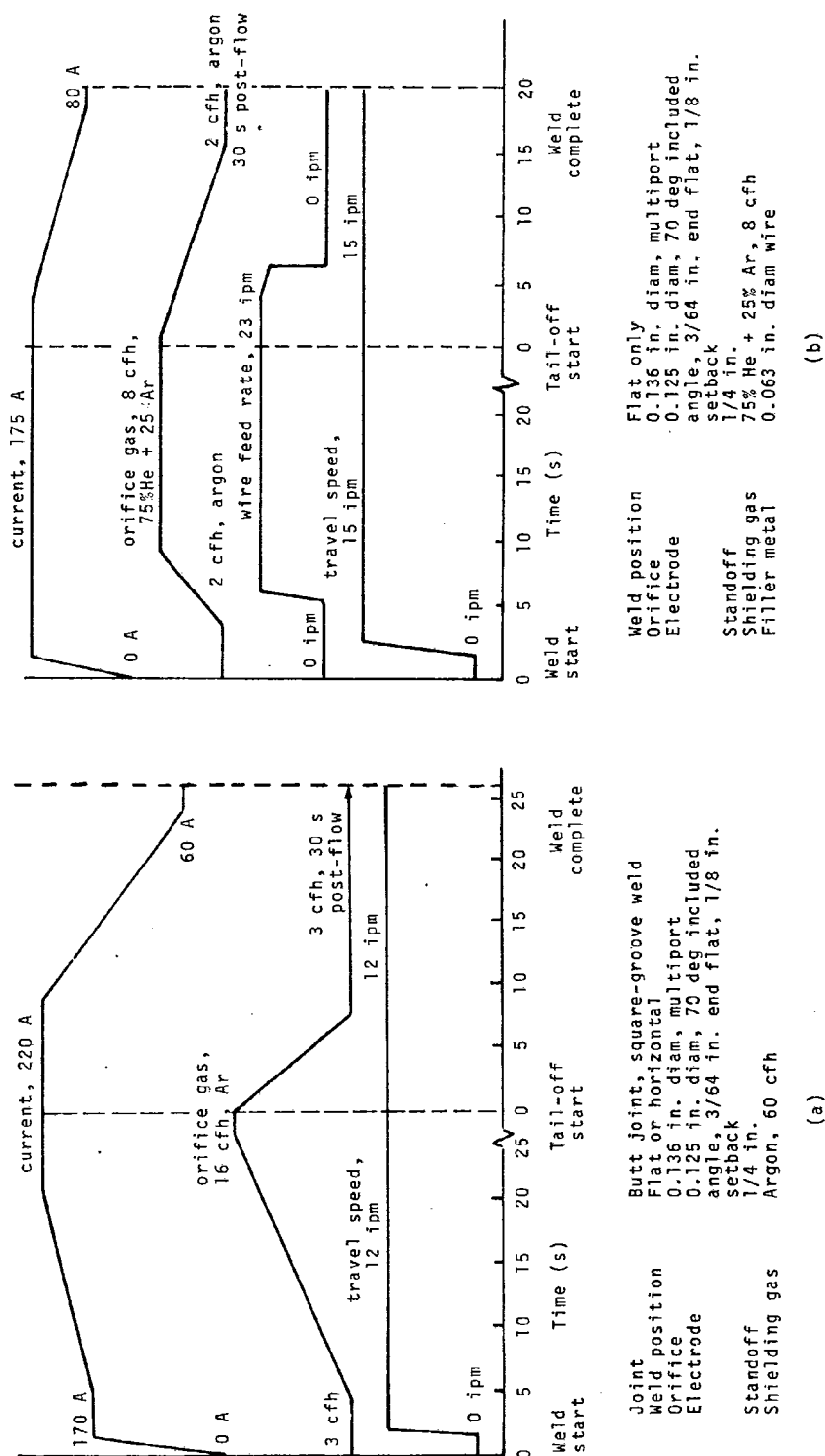
Table 10 — Typical plasma-arc welding conditions for welding stainless steels—low amperage

| Thickness<br>(in.) | Type of<br>Weld                   | Travel<br>Speed<br>(ipm) | Current<br>dcsp<br>(A) | Orifice<br>Diam<br>(in.) | Gas Flow<br>Orificed, b, c<br>(cfh) | Torch<br>Standoff<br>(in.) | Electrode<br>Diam<br>(in.) | Remarks                                                       |
|--------------------|-----------------------------------|--------------------------|------------------------|--------------------------|-------------------------------------|----------------------------|----------------------------|---------------------------------------------------------------|
| 0.030              | Square-groove weld,<br>butt joint | 5.0                      | 11                     | 0.030                    | 0.6                                 | 0.250                      | 0.40                       | Mechanized                                                    |
| 0.060              | Square-groove weld,<br>butt joint | 5.5                      | 28                     | 0.047                    | 0.8                                 | 0.250                      | 0.060                      | Mechanized                                                    |
| 0.030              | Fillet weld, tee<br>joint         | ---                      | 8                      | 0.030                    | 0.6                                 | 0.250                      | 0.040                      | Manual, filler<br>metal - 0.045 in.<br>310 stainless<br>steel |
| 0.060              | Fillet weld, tee<br>joint         | ---                      | 22                     | 0.047                    | 0.08                                | 0.250                      | 0.060                      | Manual, filler<br>metal - 0.045 in.<br>310 stainless<br>steel |
| 0.030              | Fillet weld, lap<br>joint         | ---                      | 9                      | 0.030                    | 0.6                                 | 0.375                      | 0.040                      | Manual, filler<br>metal - 0.045 in.<br>310 stainless<br>steel |
| 0.060              | Fillet weld, lap<br>joint         | ---                      | 22                     | 0.047                    | 0.8                                 | 0.375                      | 0.060                      | Manual, filler<br>metal - 0.055 in.<br>310 stainless<br>steel |

aOrifice gas - Argon.

bShielding gas - 95% Ar, 5% H at 20 cfh.

cGas underbead shielding - Argon at 10 cfh.



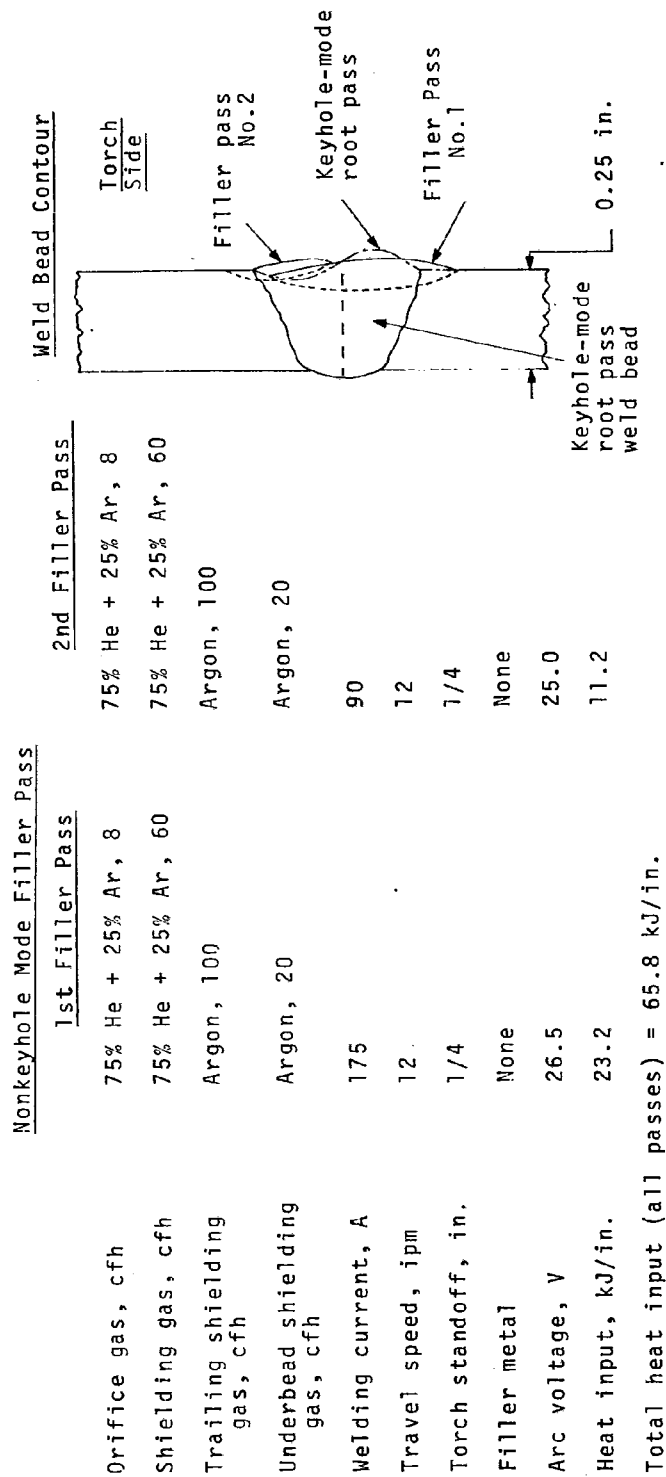


Fig. 15 - Welding conditions for horizontal position welds in titanium.

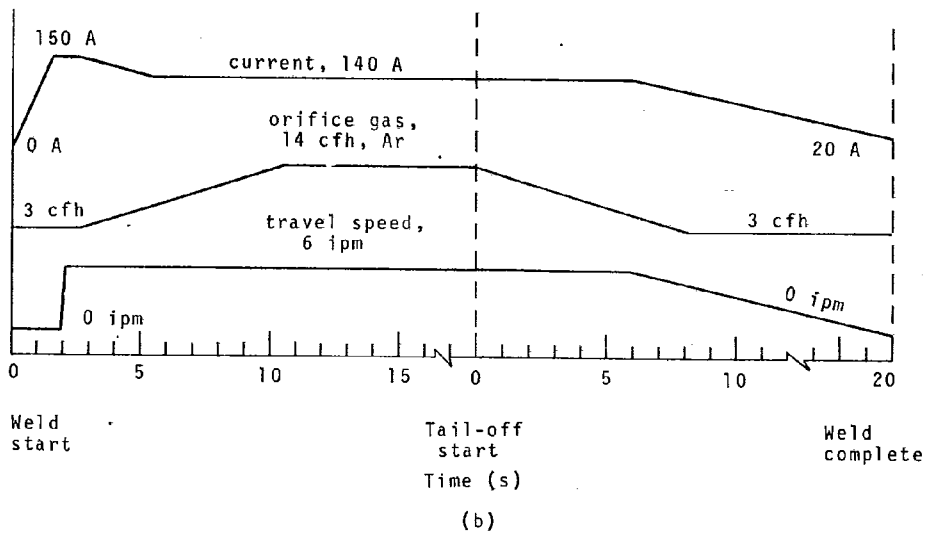
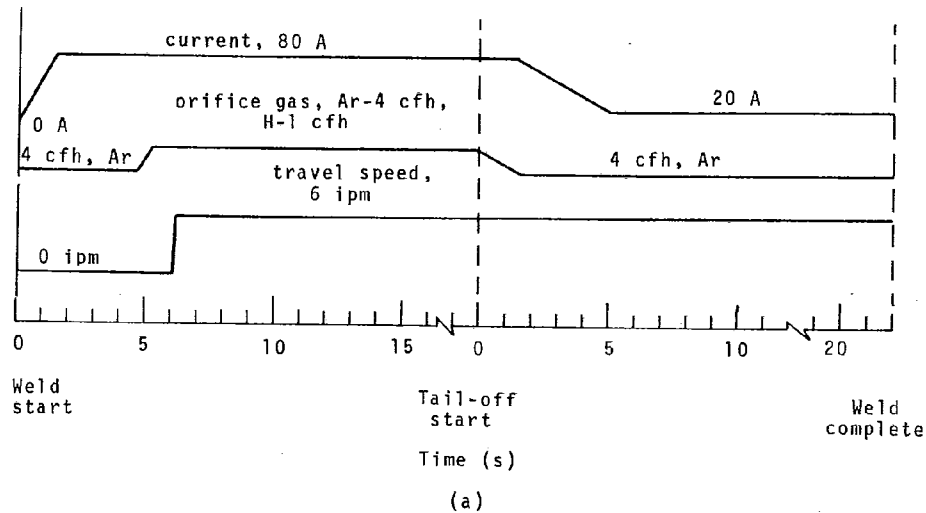
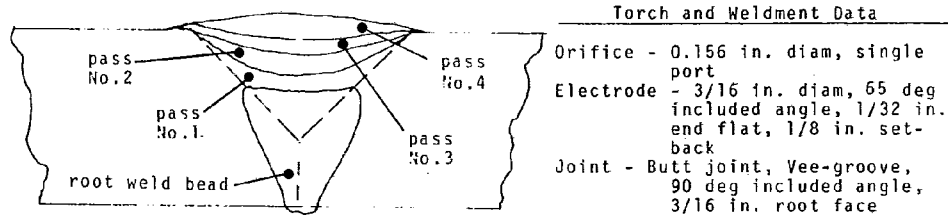


Fig. 16 – Start and tail-off conditions for single pass, flat position, square-groove welds in a butt joint, without filler metal addition, in 0.25 in. thick Inconel 718 plate. (a) Keyhole-mode weld without filler metal addition. (b) Nonkeyhole-mode filler pass without filler metal addition.





## Torch and Weldment Data

Orifice - 0.156 in. diam, single port  
 Electrode - 3/16 in. diam, 65 deg included angle, 1/32 in. end flat, 1/8 in. set-back  
 Joint - Butt joint, Vee-groove, 90 deg included angle, 3/16 in. root face

## Welding Mode and Type of Weld Pass

| Welding Variables                | Keyhole-mode root pass | Nonkeyhole-mode filler passes |                 |                 |                 |
|----------------------------------|------------------------|-------------------------------|-----------------|-----------------|-----------------|
|                                  |                        | Pass No. 1                    | Pass No. 2      | Pass No. 3      | Pass No. 4      |
| Current (A)                      | 250                    | 220                           | 200             | 200             | 220             |
| Travel speed (ipm)               | 6                      | 6                             | 6               | 6               | 5               |
| Arc voltage (V)                  | 25.0                   | 27.5                          | 26.5            | 27.5            | 26.5            |
| Orifice gas (cfh)                | 7 <sup>b</sup>         | 8 <sup>c</sup>                | 8 <sup>c</sup>  | 8 <sup>c</sup>  | 8 <sup>c</sup>  |
| Shielding gas (cfh)              | 60 <sup>b</sup>        | 60 <sup>c</sup>               | 60 <sup>c</sup> | 60 <sup>c</sup> | 60 <sup>c</sup> |
| Torch standoff (in.)             | 5/32                   | 3/16                          | 3/16            | 1/4             | 1/4             |
| Filler metal                     | None                   | d                             | d               | d               | d               |
| Wire feed (ipm)                  | ----                   | 80                            | 80              | 80              | 80              |
| Heat input <sup>a</sup> (kJ/in.) | 62.5                   | 61.0                          | 53.0            | 55.0            | 70.0            |

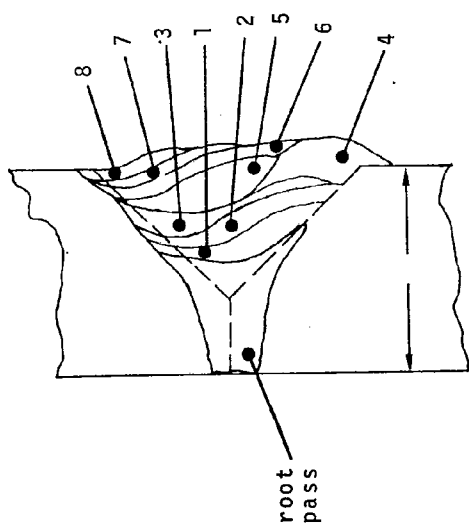
<sup>a</sup>Total heat input - 301.5 kJ/in.

<sup>b</sup>Gas used - argon.

<sup>c</sup>Gas used - 75 He, 25 Ar.

<sup>d</sup>Filler metal - 18 Ni-200 Grade maraging steel, 0.045 in. diam.

Fig. 18 - Welding conditions and variables for flat position welds in 0.60 in. thick 18 Ni steel plate.

Filler Pass SequenceTorch and Weldment Data

Orifice - 0.156 in. diam, single port  
 Electrode - 3/16 in. diam, 65 deg included angle, 1/32 in. end flat, 1/8 in. set-back  
 Joint - Butt joint, Vee-groove, 90 deg included angle, 3/16 in. root face

Welding Mode and Type of Weld Pass

| Welding Variables  | Keyhole-mode root pass | Nonkeyhole-mode filler passes |            |            |            |            |            |            |            |
|--------------------|------------------------|-------------------------------|------------|------------|------------|------------|------------|------------|------------|
|                    |                        | Pass No. 1                    | Pass No. 2 | Pass No. 3 | Pass No. 4 | Pass No. 5 | Pass No. 6 | Pass No. 7 | Pass No. 8 |
| Current (A)        | 250                    | 180                           | 170        | 170        | 160        | 160        | 160        | 150        | 110        |
| Travel speed (ipm) | 6                      | 6                             | 7          | 7          | 7          | 8          | 9          | 10         | 6          |

Fig. 19 -- Welding conditions and variables for horizontal position welds in 0.60 in. thick 18 Ni steel plate.

| Welding Variables                | Welding Mode and Type of Weld Pass |                 |                               |                 |                 |                 |                 |                 |  |  |  |  |  |  |  |  |
|----------------------------------|------------------------------------|-----------------|-------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|--|--|--|--|--|--|--|--|
|                                  | Keyhole-mode root pass             |                 | Nonkeyhole-mode filler passes |                 |                 |                 |                 |                 |  |  |  |  |  |  |  |  |
|                                  | Pass No. 1                         | Pass No. 2      | Pass No. 3                    | Pass No. 4      | Pass No. 5      | Pass No. 6      | Pass No. 7      | Pass No. 8      |  |  |  |  |  |  |  |  |
| Arc voltage (V)                  | 27.5                               | 26.7            | 25.7                          | 25.0            | 24.5            | 24.5            | 24.0            | 23.5            |  |  |  |  |  |  |  |  |
| Orifice gas (cfh)                | 8 <sup>c</sup>                     | 8 <sup>c</sup>  | 8 <sup>c</sup>                | 8 <sup>c</sup>  | 8 <sup>c</sup>  | 8 <sup>c</sup>  | 8 <sup>c</sup>  | 8 <sup>c</sup>  |  |  |  |  |  |  |  |  |
| Shielding gas (cfh)              | 60 <sup>c</sup>                    | 60 <sup>c</sup> | 60 <sup>c</sup>               | 60 <sup>c</sup> | 60 <sup>c</sup> | 60 <sup>c</sup> | 60 <sup>c</sup> | 60 <sup>c</sup> |  |  |  |  |  |  |  |  |
| Torch standoff (in.)             | 3/16                               | 3/16            | 3/16                          | 1/8             | 1/8             | 3/16            | 3/16            | 3/16            |  |  |  |  |  |  |  |  |
| Filler metal                     | d                                  | d               | d                             | d               | d               | d               | d               | d               |  |  |  |  |  |  |  |  |
| Wire feed (ipm)                  | 80                                 | 80              | 60                            | 60              | 60              | 60              | 60              | 36              |  |  |  |  |  |  |  |  |
| Heat input <sup>a</sup> (kJ/in.) | 49.5                               | 38.9            | 37.4                          | 34.2            | 29.4            | 26.1            | 21.6            | 25.8            |  |  |  |  |  |  |  |  |

<sup>a</sup>Total heat input - 325.4 kJ/in.

<sup>b</sup>Gas used - argon.

<sup>c</sup>Gas used - 75% He, 25% Ar.

<sup>d</sup>Filler metal - 18 Ni-200 Grade maraging steel, 0.45 in. diam wire.

Fig. 19 (continued) - Welding conditions and variables for horizontal position welds in 0.60 in. thick 18 Ni steel plate.

## 40 / PLASMA-ARC WELDING PRACTICES

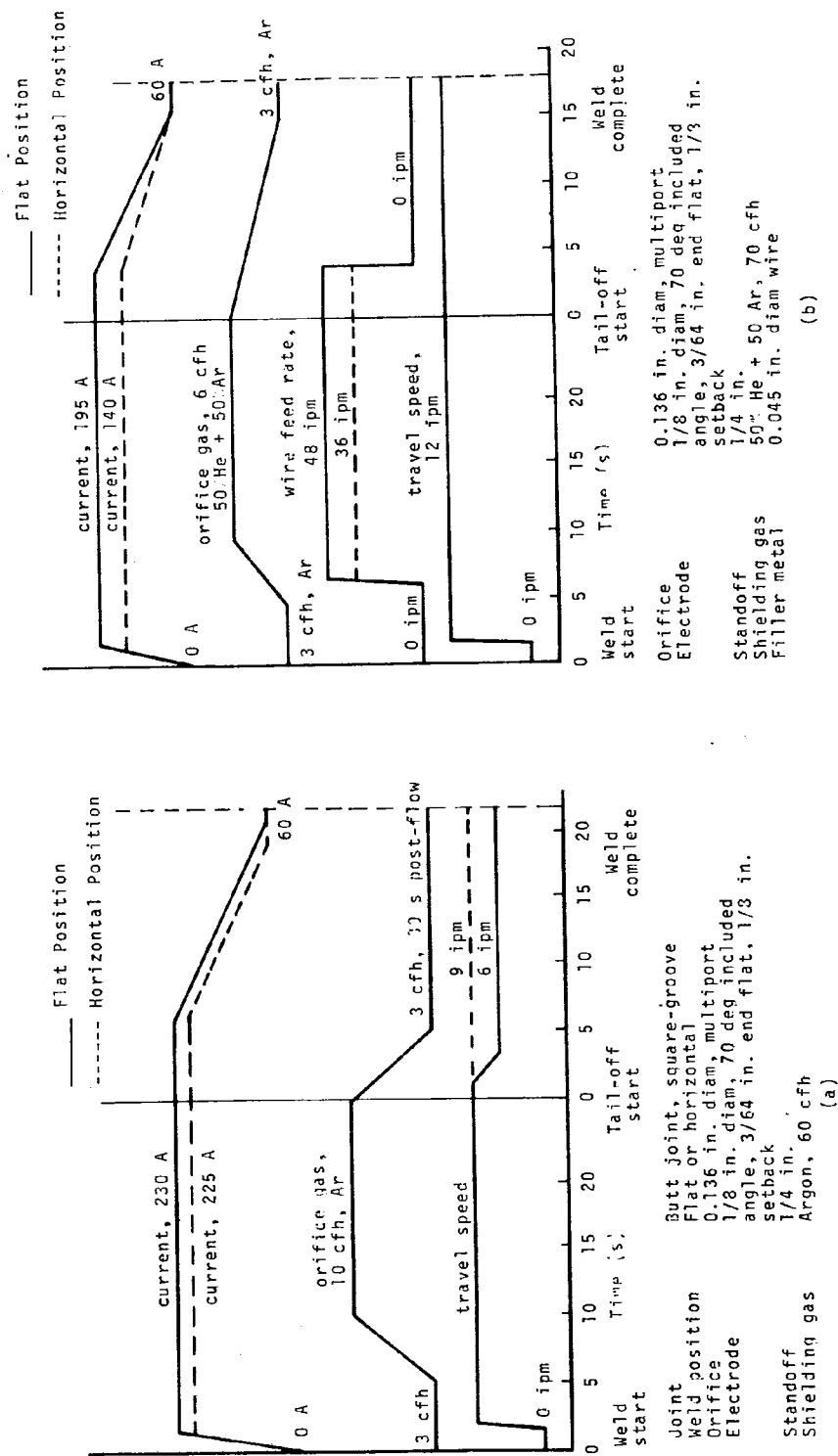
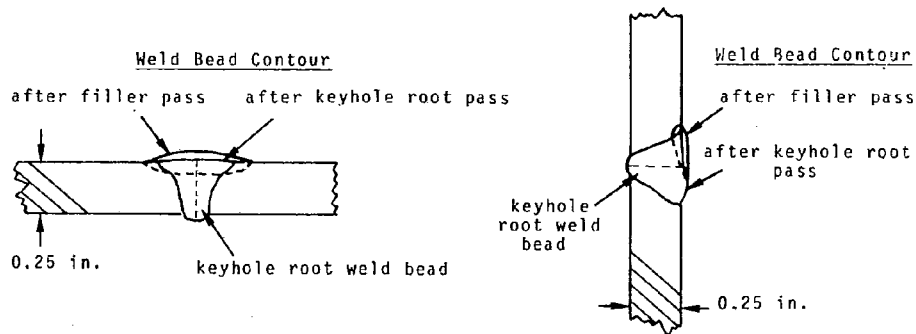


Fig. 20 - Welding conditions and timing for continuous circumferential plasma-arc welds in 0.25 in. 18 Ni steel. (a) Start and tail-off conditions for keyhole-mode welds. (b) Start and tail-off conditions for nonkeyhole-mode filler welds.



Torch and Weldment Data for Flat and Horizontal Position Welds

Orifice - 0.136 in. diam multiport  
 Electrode - 0.125 in. diam, 70 deg included angle, 3/64 in. end flat,  
 1/8 in. setback  
 Joint - Butt joint, square-groove

| Welding Variables                         | Position of Welding    |                             |                        |                             |
|-------------------------------------------|------------------------|-----------------------------|------------------------|-----------------------------|
|                                           | Flat position          |                             | Horizontal position    |                             |
|                                           | Keyhole-mode root pass | Nonkeyhole-mode filler pass | Keyhole-mode root pass | Nonkeyhole-mode filler pass |
| Current (A)                               | 230                    | 195                         | 225                    | 140                         |
| Travel speed (ipm)                        | 9                      | 12                          | 9                      | 12                          |
| Arc voltage (V)                           | 26.0                   | 24.0                        | 25.9                   | 23.0                        |
| Orifice gas (cfh)                         | 10 <sup>a</sup>        | 6 <sup>b</sup>              | 10 <sup>a</sup>        | 6 <sup>b</sup>              |
| Shielding gas (cfh)                       | 60 <sup>a</sup>        | 70 <sup>b</sup>             | 60 <sup>a</sup>        | 70 <sup>b</sup>             |
| Torch standoff (in.)                      | 1/4                    | 1/4                         | 1/4                    | 1/4                         |
| Filler metal                              | none                   | c                           | none                   | c                           |
| Wire feed (ipm)                           | ----                   | 46                          | ----                   | 36                          |
| Heat input (kJ/in.)                       | 39.9                   | 23.4                        | 38.8                   | 16.1                        |
| Total heat input for both passes (kJ/in.) | 63.3                   |                             | 54.9                   |                             |

<sup>a</sup>Gas used - argon.

<sup>b</sup>Gas used - 50% He, 50% Ar.

<sup>c</sup>Filler metal - 0.045 in. diam wire.

Fig. 21 - Welding conditions and weld bead placement for flat and horizontal position plasma-arc welds in 0.25 in. thick 18 Ni steel plate.

### 5.10 Multipass Welding

**5.10.1** A multipass plasma-arc weld involves a keyhole-mode root pass and one or more nonkeyhole-mode filler passes, with or without filler metal addition. The nonkeyhole-mode plasma arc uses a plasma in which the force of the plasma stream has been substantially reduced. Total orifice-gas flow rate is reduced, torch standoff is increased. Varying percentages of helium or hydrogen gas may be mixed with argon in the orifice- and shielding-gas circuits to cause the arc heat to dissipate over a larger surface area on the weld joint. Helium can be used, and is favored, for some applications because it provides a broader heat-input pattern and produces a flatter filler pass weld bead. The very wide range of weld penetration characteristics attainable, using these techniques with the high-current plasma arc, provides substantially greater process flexibility than is available with other gas-shielded arc-welding processes.

### 5.11 Reverse Polarity Welding

**5.11.1** Tungsten electrodes exhibit reduced current capacity when connected for reverse polarity operation — whether they are used for plasma-arc or gas tungsten-arc welding. Therefore, a water-cooled electrode is preferable for reverse polarity welding. Compared to the arcs encountered in reverse polarity gas tungsten-arc operation, the plasma jet produces an inherently stable arc. A single port nozzle is generally used for reverse polarity work because multiport nozzles do not provide the advantages realized with straight polarity welding.

### 5.12 Recommended Practices

**5.12.1** Metals to be joined, joint configuration, and thickness are the major considerations for plasma-arc welding.

**5.12.2** The requirements for metal cleanliness, edge alignment, fitup, and the tolerance for mismatch for plasma-arc welding are commensurate with the quality required and the general welding results. Preheat and postweld thermal treatments and heating are similar to other processes and dependent upon metallurgical considerations for the base metals.

**5.12.3** Tables 3 through 10 and Figs. 14 through 21 are grouped by metals. The plasma-arc welding conditions listed are recommended as nominal for the thicknesses and applications noted. These data are a summation of conditions used in production and process development for both low-current manual and high-current mechanized applications.

### 5.13 Advantages and Limitations

#### 5.13.1 Sensitivity to Changes in Arc Length

**5.13.1.1** The collimated shape of the low-current plasma jet is chiefly responsible for the lack of process sensitivity to changes in arc length. Figure 22 shows a low-current plasma arc operating at ten amperes. The plasma arc emerges from a 0.030 in. diameter nozzle and is 1/4 in. long. The total included angle of divergency is 6 deg in the low-current plasma arc.

**5.13.1.2** Arc cross-sectional area and total arc current establish the average current density at any location in the arc. Current density establishes the rate at

which heat is transferred to a unit area of weld puddle or work surface when the work is placed at a given location. Thus a well-collimated arc can tolerate relatively large variations in arc length before its melting capability is affected seriously. This usually obviates the need for sensing and maintaining a constant length. The longer permissible torch-to-work distance affords the welder better visibility.

**5.13.1.3** Returning to the arcs in Fig. 22 and assuming that a change in arc cross-sectional area of 20% can be tolerated, measurements and calculations show that the low-current plasma-arc length can be varied by  $\pm 0.05$  in. without significantly affecting weld width and penetration.

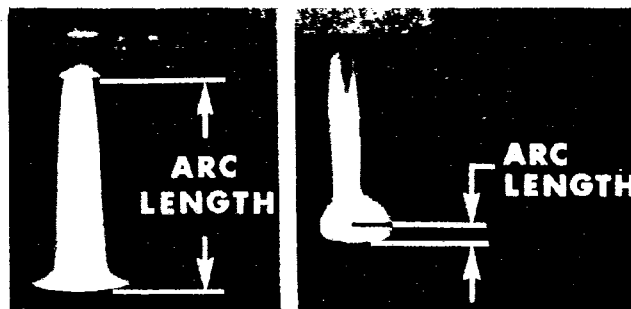


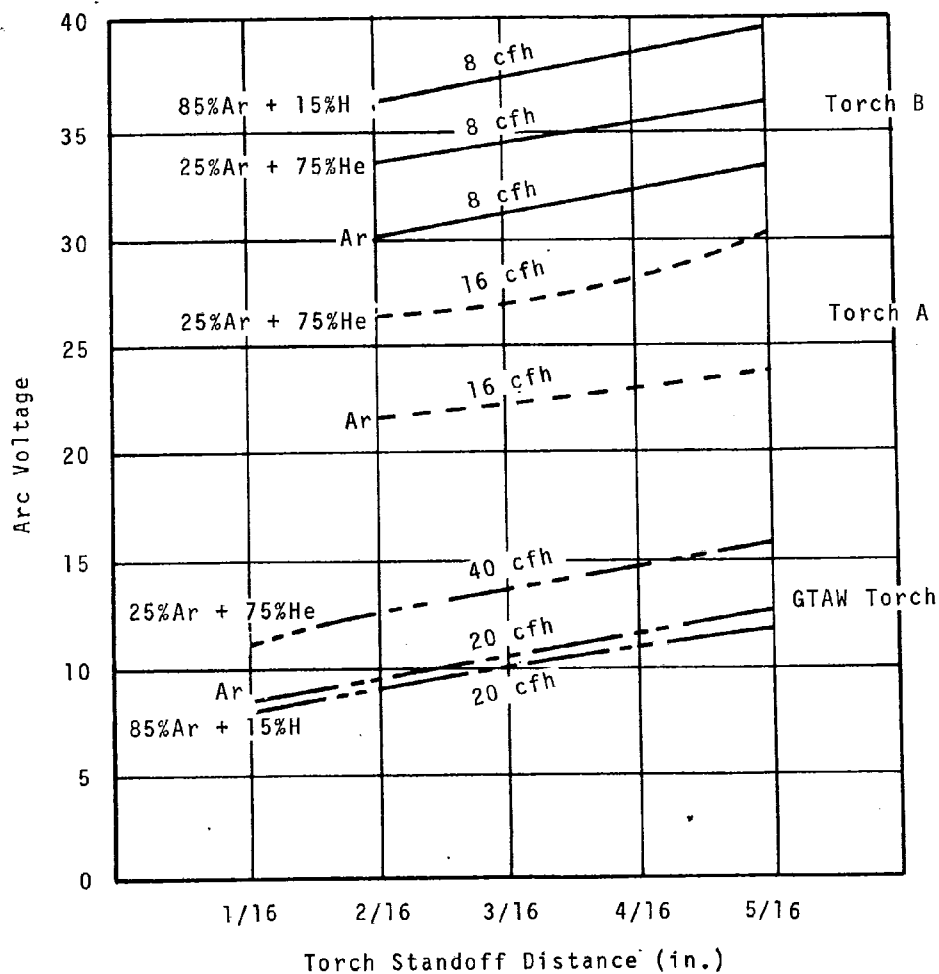
Fig. 22 – Comparison of 10 A plasma arc and gas tungsten-arc at arc lengths commonly used for welding very thin metal sections: left, low-current plasma arc is 0.25 in. long; right, gas tungsten-arc is 0.025 in. long.

### 5.13.2 Arc-Voltage Controls

**5.13.2.1** The relative insensitivity of the plasma-arc welding process to arc length variations usually obviates the need for arc-voltage equipment for many commercial applications. However, arc-voltage control has been used with plasma-arc welding to follow contoured weldments. It is necessary to lock out the height control when current or orifice-gas sloping is employed because varying these settings causes corresponding changes in arc voltage. Thus, due to the sloping of these functions, marked changes in arc voltage can occur even though the torch-to-work distance remains constant. Figure 23 illustrates the slope similarity in arc length/arc voltage curves for plasma-arc and gas tungsten-arc torches.

**5.13.2.2** The use of fixed reference voltage settings in applications of automatic arc-voltage control equipment with commercial high-current plasma-arc torches may be complicated by voltage repeatability considerations. Small variations in electrode point configuration, setback and centering, orifice-gas flow rate, and tolerances of orifices may cause variations in arc voltage.

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- Note: (a) The orifice gas flow rates for all plasma-arc torches were held at values indicated above on a flowmeter calibrated for pure argon gas.
- (b) The gas flow rates shown above for the GTAW torch were for the shielding gas.

Fig. 23 - Arc voltage characteristics of three torches for three different arc plasma support gases, using arc conditions for welding 0.25 in. thick plate.

### 5.13.3 Electrode Contamination

**5.13.3.1** Because the electrode in the plasma-arc torch is recessed within the arc-constricting nozzle, it is not possible to touch the electrode to the workpiece. This property greatly reduces the possibility of tungsten inclusions in the weld and can substantially extend the period between electrode dressings. The life of the electrode is also improved by a constant flow of inert orifice gas which minimizes erosion of the electrode.

### 5.13.4 Keyhole Effect

**5.13.4.1** One of the chief differences between the plasma-arc and gas tungsten-arc welding processes is the "keyhole" effect. It can be obtained with the plasma arc when making square-groove welds in butt joints in certain thicknesses of most metals. The keyhole is a positive indication of complete penetration and weld uniformity. For details, see 3.1.3.

**5.13.4.2** Many metallurgical advantages are possible with the keyhole mode. The smaller heat-affected zone reduces strength loss at the joint for heat-treated metals, and promotes less grain growth which results in better ductility. The reduced welding time interval results in less embrittlement by carbides and complex intermetallic compounds for stainless steels and superalloys. Further, the equalizing of distortion stresses — top to bottom of the weld cross section — results in less residual stress. The surface condition in prepared joints and on filler metals is a major factor in causing porosity. Because the plasma-arc welding process requires less filler metal in the keyhole mode, porosity is significantly reduced when making simple square-groove butt welds by this method.

**5.13.4.3** The greater penetrating power of the plasma jet, as compared to gas tungsten-arc welding, can be used to produce a higher depth-to-width ratio in the weld.

### 5.13.5 Fabrication Advantages

**5.13.5.1** Various fabrication advantages are possible with the plasma-arc welding process. They include fewer weld passes, reduced cost for filler metal, and decreased possibility of human error due to less manipulation in general. Another advantage is that need for interpass cleaning, back-gouging, and temperature maintenance, if needed, are needed less. For keyholing applications, machining is reduced in making a square-groove type joint preparation instead of a Vee- or a U-type. Tooling can be simpler and therefore less costly because distortion tendencies are reduced.

### 5.13.6 Process Limitations

**5.13.6.1** The plasma-arc welding process is limited in application to a maximum metal thickness of one inch in making butt welds. Further development is needed to extend its application to thicker sections. Mechanized plasma-arc welding is generally used in the flat and horizontal positions although development in vertical welding has been satisfactory. Manual plasma-arc welding can be used in all positions.

## 6. Application of the Plasma-Arc Welding Process to Surfacing

### 6.1 General Considerations

**6.1.1** Surfacing is applied to metals for improved resistance to abrasion, corrosion, or for improved impact properties not ordinarily displayed by the base metal. It can also be used for replacement of worn or corroded metal. Consideration must be given to the filler metal, deposition rate required, maximum dilution permitted with the base metal, and the thickness or quantity of the deposited metal. Table 11 illustrates results obtained with various welding processes in their application to surfacing.

**6.1.2** Since plasma-arc weld surfacing is a fusion process, it is necessary to follow the same preheating, postheating, and slow cooling procedures specified for welding certain types of base metals. In general, the higher the alloy content and the larger the workpiece, the more heating and other precautions are necessary. Also, large differences in thermal expansion coefficients between the base metal and the filler metal should be avoided to minimize the possibility of cracking.

### 6.2 Powder Surfacing

#### 6.2.1 Operational Characteristics

**6.2.1.1** A standard powder surfacing torch is used to apply overlays from 1/64 in. to 1/8 in. thick at currents up to 250 amperes. Stringer beads as narrow as 3/64 in. can be made, and beads as wide as 1 3/4 in. can be produced by oscillating the torch. A schematic of a standard powder surfacing torch is shown in Fig. 9. By replacing the lower section of the torch with a heavy-duty nozzle assembly, deposits up to 1/4 in. thick can be made at currents up to 350 amperes. The heavy-duty assembly also provides means for separately depositing large-size wear-resistant particles such as tungsten carbide into a weld deposit to produce heterogeneous deposits. An additional tungsten carbide dispensing unit is required for this application. A relatively low flow of argon (between 3 and 10 cfh) is directed through the constricting orifice to minimize weld penetration and dilution. Heating of the puddle on the workpiece, which determines the extent of weld dilution, is controlled by adjusting the transferred-arc current from the transferred-power supply.

#### 6.2.2 Effects on the Base Metal

**6.2.2.1** Plasma-arc deposits solidify from the molten state into a dense cast structure. Consequently, the metallurgical properties of these deposits are similar to those of gas tungsten-arc overlays. The depth of the heat-affected zone is a function of the rate of heat input and the chill produced by the base metal. On nonpreheated base metal 1/4 in. thick and heavier, the depth of the heat-affected zone is approximately equivalent to the thickness of the deposit. On thinner sections, the base metal structure will be affected throughout its thickness unless cooling means are used.

#### 6.2.3 Filler Metal

**6.2.3.1** A wide variety of cobalt-, nickel-, and iron-base alloys is available in powder form for powder surfacing with the plasma-arc welding process. They

Table 11 — Comparison chart for various surfacing operations

| Process                        | Deposition<br>Rate<br>Normal Range<br>(lb/h) | Weld<br>Dilution<br>Normal Range <sup>a</sup><br>(%) | Minimum<br>Practical<br>Deposit<br>Thickness <sup>b</sup><br>(in.) | Filler<br>Metal<br>Form |
|--------------------------------|----------------------------------------------|------------------------------------------------------|--------------------------------------------------------------------|-------------------------|
|                                |                                              |                                                      |                                                                    |                         |
| Oxyacetylene                   | 1 - 6                                        | 1 - 10                                               | 0.031                                                              | Rod, powder             |
| Gas Tungsten-Arc               | 1 - 8                                        | 10 - 15                                              | 0.094                                                              | Rod, wire               |
| Plasma-Arc (powder)            | 1 - 15                                       | 5 - 30                                               | 0.015 <sup>c</sup>                                                 | Powder                  |
| Submerged Arc (single wire)    | 10 - 12                                      | 30 - 60                                              | 0.125                                                              | Wire                    |
| Submerged Arc (series circuit) | 25 - 35                                      | 15 - 35                                              | 0.188                                                              | Wire                    |
| Gas Metal-Arc (single wire)    |                                              |                                                      |                                                                    |                         |
| Short-Circuit Transfer         | 2 - 6                                        | 10 - 25                                              | 0.063                                                              | Wire                    |
| Spray-Type Transfer            | 8 - 15                                       | 20 - 70                                              | 0.125                                                              | Wire                    |
| Gas Metal-Arc (auxiliary wire) | 20 - 30                                      | 15 - 30                                              | 0.188                                                              | Wire                    |
| Plasma-Arc (two hot wires)     | 35 - 60                                      | 5 - 20                                               | 0.094                                                              | Wire                    |
| Plasma-Arc (single hot wire)   | 5 - 15                                       | 5 - 20                                               | 0.094                                                              | Wire                    |

<sup>a</sup>Single layer deposits.<sup>b</sup>Maximum practical single pass deposit thickness in all cases is 1/4 in. Multipasses are used for thicker overlays.<sup>c</sup>Obtainable using self-fluxing (boron/silicon containing) alloys.

Table 12 — Nominal powder compositions and hardness of deposits for plasma-arc weld surfacing

| Chemical Compositions, <sup>a</sup> |      |                   |                   |       |                   |                   |                   |        |        |                                   |
|-------------------------------------|------|-------------------|-------------------|-------|-------------------|-------------------|-------------------|--------|--------|-----------------------------------|
| Cr                                  | C    | Si                | Mn                | Mo    | Fe                | Ni                | Co                | B      | W      | Deposit<br>Hardness<br>Rockwell C |
| Cobalt-Base                         |      |                   |                   |       |                   |                   |                   |        |        |                                   |
| 30.00                               | 2.40 | 1.00              | 0.50 <sup>b</sup> | ....  | 3.00 <sup>b</sup> | 3.00 <sup>b</sup> | Bal.              | ....   | 12.50  | 48                                |
| 28.00                               | 1.00 | 1.00              | 1.00 <sup>b</sup> | ....  | 3.00 <sup>b</sup> | 3.00 <sup>b</sup> | Bal.              | ....   | 4.00   | 37                                |
| 30.00                               | 1.40 | 1.45              | 1.00 <sup>b</sup> | ....  | 3.00 <sup>b</sup> | 3.00 <sup>b</sup> | Bal.              | ....   | 8.25   | 41                                |
| 27.00                               | 0.25 | 1.00 <sup>b</sup> | 1.00 <sup>b</sup> | 5.50  | 2.00 <sup>b</sup> | 2.50              | Bal.              | ....   | ....   | 32                                |
| 20.00                               | 0.01 | 1.00 <sup>b</sup> | 1.00 <sup>b</sup> | ....  | 3.00 <sup>b</sup> | 10.00             | Bal.              | ....   | 15.00  | 22                                |
| 28.00                               | 1.60 | 1.15              | 1.00 <sup>b</sup> | ....  | 0.50 <sup>b</sup> | 33.00             | Bal.              | ....   | 4.00   | 43                                |
| 25.25                               | 0.50 | 1.00 <sup>b</sup> | 1.00 <sup>b</sup> | ....  | 2.00 <sup>b</sup> | 10.50             | Bal.              | ....   | 7.50   | 32                                |
| 25.00                               | 1.70 | 0.95              | 1.00 <sup>b</sup> | ....  | 1.10              | 22.00             | Bal.              | ....   | 12.00  | 35                                |
| 21.00                               | 0.07 | 1.60              | .... <sup>b</sup> | ....  | ....              | ....              | Bal.              | 2.40   | 4.50   | 52                                |
| 25.50                               | 0.75 | 1.25              | 1.00 <sup>b</sup> | ....  | 0.75              | .... <sup>b</sup> | Bal.              | 0.70   | 4.00   | 43                                |
| 26.00                               | 3.25 | 1.00 <sup>b</sup> | 0.50 <sup>b</sup> | ....  | 5.00 <sup>b</sup> | 3.00 <sup>b</sup> | Bal.              | ....   | 14.00  | 50                                |
| 32.00                               | 2.50 | 1.00              | 1.00 <sup>b</sup> | ....  | 3.00 <sup>b</sup> | 2.50 <sup>b</sup> | Bal.              | ....   | 17.00  | 52                                |
| Nickel-Base                         |      |                   |                   |       |                   |                   |                   |        |        |                                   |
| 11.00                               | 0.45 | 2.25              | 0.50 <sup>b</sup> | ....  | 2.25              | Bal.              | 1.50 <sup>b</sup> | 2.50   | ....   | 46                                |
| 14.00                               | 0.75 | 4.00              | 1.00 <sup>b</sup> | ....  | 4.00              | Bal.              | 1.00 <sup>b</sup> | 3.25   | ....   | 54                                |
| 17.00                               | 0.95 | 3.90              | 0.50 <sup>b</sup> | ....  | 2.00              | Bal.              | 1.00 <sup>b</sup> | 3.30   | ....   | 54                                |
| 9.00                                | 0.45 | 3.00              | 1.00 <sup>b</sup> | ....  | 3.75              | Bal.              | 1.00 <sup>b</sup> | 2.00   | ....   | 40                                |
| Iron-Base                           |      |                   |                   |       |                   |                   |                   |        |        |                                   |
| 27.00                               | 2.75 | 1.00 <sup>b</sup> | 1.00 <sup>b</sup> | ....  | Bal.              | ....              | ....              | ....   | ....   | 52                                |
| 1.50 <sup>b</sup>                   | 3.75 | 1.00 <sup>b</sup> | 1.00 <sup>b</sup> | 10.00 | Bal.              | ....              | ....              | ....   | ....   | 60                                |
| 17.00                               | 3.00 | 1.50 <sup>b</sup> | 0.50 <sup>b</sup> | 16.00 | Bal.              | ....              | 6.25              | ....   | V-1.90 | 55                                |
| 26.00                               | 2.65 | 1.30              | 1.00 <sup>b</sup> | ....  | Bal.              | ....              | 3.00              | 0.75   | ....   | 63                                |
| 33.00                               | 3.20 | 2.00              | 1.00 <sup>b</sup> | ....  | Bal.              | ....              | 8.20              | 1.80   | ....   | 62                                |
| 5.00                                | 1.00 | 0.50 <sup>b</sup> | 0.50 <sup>b</sup> | 6.25  | Bal.              | ....              | ....              | V-2.70 | 7.50   | 64                                |

<sup>a</sup>Single layer 0.100 in. thick deposits on SAE 1020 Steel..

<sup>b</sup>Maximum.

<sup>a</sup>Single layer 0.100 in. thick deposits on SAE 1020 Steel..<sup>b</sup>Maximum.

are listed in Table 12 along with typical deposit hardness values. The powders are classed as high-alloy types and have varying degrees of abrasion, impact, and corrosion resistance.

#### 6.2.4 Recommended Practices

**6.2.4.1** The relationship between welding conditions can be seen in Fig. 24. These characteristic curves for a surfacing alloy consisting of 64% cobalt, 30% chromium, and 4% tungsten indicate that, for a given deposit thickness, weld dilution increases as the deposition rate increases. This is logical because the increased current required to increase the deposition rate causes an increase in weld depth of fusion. The curves also show that, for a given deposition rate, weld dilution decreases as the deposit thickness increases. The heavier deposit, with its larger weld puddle, acts as a buffer to reduce arc penetration and thus decreases dilution.

**6.2.4.2** The curves in Fig. 24 are useful from the practical viewpoint because they show that the metal deposition rate is limited by the required deposit thickness and the tolerable dilution level. For example, if the desired deposit thickness of the Co-Cr-W alloy is 1/8 in. and the dilution cannot exceed 10%, the maximum deposition rate is automatically fixed at about 3 lb/h. However, if a dilution level of 20% is acceptable, a deposition rate of more than 6 lb/h can be used. Typical process settings for depositing a variety of widths and thicknesses are shown in Table 13.

**6.2.4.3** The effect of alloy composition on the relationship between surfacing conditions can be seen by comparing the curves in Fig. 24a to those in Fig. 24b. The latter set of curves was obtained using a filler metal similar to that used to obtain the curves in Fig. 24a — except a small percentage of boron was added to the powder. Boron reduces the melting point of the alloy and improves its wetting characteristics, thereby effecting a desirable downward shift in the family of curves. This means that with the boron-bearing alloy, thinner deposits can be made at lower dilution levels than with the Co-Cr-W alloy. Note that for a 1/8 in. thick deposit at 10% dilution, the allowable deposition rate is 9 lb/h for the Co-Cr-W-B alloy compared to 3 lb/h for the Co-Cr-W alloy.

#### 6.2.5 Advantages

**6.2.5.1** Powder surfacing with the plasma-arc welding process can be used to achieve high metal-deposition rates, low base-metal dilution, and unusually thin deposits. Deposition rates can be controlled from less than 1 lb/h to more than 12 lb/h at dilution levels of 5 to 30 percent. A significant advantage of powder surfacing, however, is its ability to use metal powders. This is important because all metals can be provided in powder form, but they cannot all be provided in rod or wire form suitable for continuous operation. Powdered cobalt-base alloys, for example, can be deposited continuously and uniformly without the limitations imposed by the use of the metal in rod form. Also, by tailoring the powder formulation, many special alloys can be prepared for depositing. For satisfactory results, the filler metal must have the same or lower melting point than the base metal.

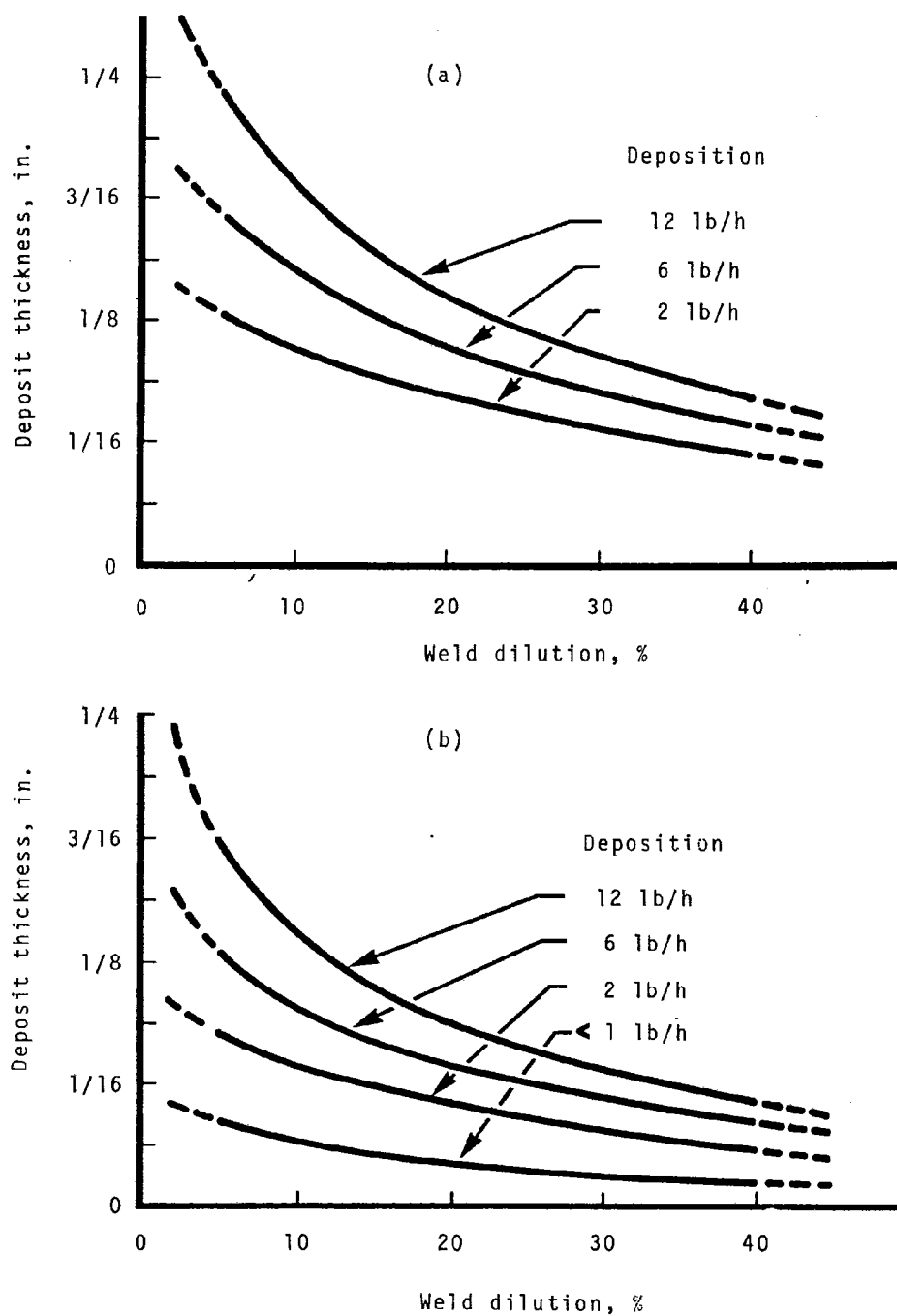


Fig. 24 - Characteristic curves for two types of alloys deposited with a plasma arc for powder surfacing. (a) Co-Cr-W alloy. (b) Co-Cr-W-B alloy.

Table 13 — Typical welding conditions for powder surfacing with the plasma-arc welding process

|                               |       |       |       |      |       |       |      |      |      |
|-------------------------------|-------|-------|-------|------|-------|-------|------|------|------|
| Deposit Width, in.            | 0.37  | 0.75  | 0.68  | 1.25 | 0.43  | 1.06  | 1.12 | 1.18 | 0.56 |
| Deposit Thickness, in.        | 0.012 | 0.065 | 0.060 | 0.21 | 0.060 | 0.062 | 0.06 | 0.18 | 0.04 |
| Torch Standoff, in.           | 7/16  | 7/16  | 3/8   | 1/2  | 7/16  | 7/16  | 1/2  | 5/8  | 1/2  |
| Surfacing Speed, ipm          | 20    | 10    | 6     | 5    | 16    | 9.6   | 18.5 | 6    | 15.3 |
| Oscillation Speed, cpm        | 210   | 180   | 120   | 100  | 170   | 127   | 200  | 120  | 200  |
| Powder Dispensing Rate, g/min | 10.7  | 31    | 33    | 126  | 65    | 55    | 160  | 140  | 44   |
| Argon Gas Flow Rate           |       |       |       |      |       |       |      |      |      |
| Orifice, cfh                  | 4     | 5     | 4     | 10   | 6     | 4     | 9    | 10   | 7    |
| Powder, cfh                   | 11    | 10    | 11    | 15   | 10    | 15    | 15   | 15   | 12   |
| Shield, cfh                   | 50    | 40    | 40    | 55   | 45    | 40    | 45   | 55   | 50   |
| Welding Current, A            | 125   | 155   | 160   | 250  | 180   | 175   | 350  | 320  | 240  |
| Welding Voltage, V            | 36    | 42    | 38    | 39   | 37    | 48    | 34   | 40   | 30   |

### 6.3 Hot-Wire Surfacing

#### 6.3.1 Operational Characteristics

**6.3.1.1** In hot-wire surfacing with the plasma-arc welding process, the two wires that are fed into the puddle are resistance heated with a current flowing in series through them. A schematic is shown in Fig. 10. This circuit is used so that the magnetic fields set up about the two wires, which might otherwise deflect the arc and cause irregularities in melting, tend to cancel each other. A constant potential a-c power source provides the resistance ( $I^2R$ ) heating of the filler metal wires. The function of the hot-wire system is to supply molten filler metal to the arc zone. A single hot-wire system may be used to obtain narrow deposits; however, deposition rates are limited to about 15 lb/h.

**6.3.1.2** The hot-wire system is independent of the plasma arc. This allows for independent adjustments in wire speed and melting rate to suit requirements of deposit thickness and deposition rate. Use of the plasma-arc torch permits control over the arc current, orifice-gas flow, and orifice size. This provides a measure of control over dilution.

**6.3.1.3** The spacing between the hot-wire guns and the work is critical because the resistance heating of the filler metal wires depends on the extension of the wires between the guns and the workpiece. If the distance is too short, the wires will not be heated sufficiently. If the distance is too long, the voltage drop across the wire extension may increase enough for an arc to occur. This will cause irregularities in the deposit. For these reasons, an arc-voltage control is usually used to maintain a constant standoff distance for the hot-wire guns.

**6.3.1.4** An argon-helium mixture is used as the orifice gas in the plasma-arc torch, and argon is used as the shielding gas. Since the filler metal wires are brought to their melting point in an argon atmosphere, they tend to outgas and thus drive off any surface contaminants which might be present. This eliminates a potential source of porosity in the overlay and produces a higher quality overlay than might be obtained with other surfacing methods utilizing filler metal addition in wire form.

#### 6.3.2 Filler Metal

**6.3.2.1** Many surfacing filler metals have been successfully applied with the plasma-arc welding process. They include austenitic and martensitic stainless steels, nickel and nickel-base alloys, and copper and copper-base alloys.

#### 6.3.3 Recommended Practices

**6.3.3.1** Hot-wire surfacing with the plasma-arc welding process is relatively simple because many of the variables remain essentially the same regardless of the deposition objectives or the metal being applied. The operation is mechanized, making surfacing conditions highly reproducible. Shielding-gas flow rates for the system, in most cases, remain the same. The plasma-arc torch standoff is adjusted for 7/8 in. by presetting the voltage control head. The oscillation width and travel speed are selected for a desired area-surfacing rate so that the volume of filler metal to be melted will produce the desired deposit thickness. For example, a 15 sq in./min (1.5 in. width  $\times$  10 ipm) area-surfacing rate will produce a 3/16 in. thick deposit when depositing filler metal at 50 lb/h. The plasma-arc and hot-wire

Table 14 — Welding conditions for hot-wire surfacing with a plasma arc

| Filler Metal Type          | Wire Size (diam.) (in.) | Deposition Rate (lb/h) | Deposit Thickness (in.) | Surfacing Speed (ipm) | Coverage (lb/ft <sup>2</sup> ) | Arc Time (min/ft <sup>2</sup> ) | Hot-Wire Current |     | Plasma-Arc Current (A) | Deposit Dilution % | Preheat Temp. (F) |
|----------------------------|-------------------------|------------------------|-------------------------|-----------------------|--------------------------------|---------------------------------|------------------|-----|------------------------|--------------------|-------------------|
|                            |                         |                        |                         |                       |                                |                                 | ac               | dc  |                        |                    |                   |
| <u>Stainless Steels</u>    |                         |                        |                         |                       |                                |                                 |                  |     |                        |                    |                   |
| 308L                       | 1/16                    | 60                     | 0.234                   | 10                    | 9.6                            | 9.6                             | 500              | 510 |                        | <2                 | 200               |
|                            |                         | 60                     | 0.218                   | 10                    | 9.6                            | 9.6                             | 500              | 560 | 2                      | 200                |                   |
|                            |                         | 60                     | 0.187                   | 10                    | 9.6                            | 9.6                             | 500              | 610 | 7.5                    | 200                |                   |
|                            |                         | 70                     | 0.218                   | 9.5                   | 10.1                           | 8.7                             | 315              | 620 | 11.7                   | 200                |                   |
| 308L                       | 3/32                    | 60                     | 0.218                   | 10                    | 9.6                            | 9.6                             | 500              | 560 | 5                      | 200                |                   |
| 347                        | 3/32                    | 60                     | 0.234                   | 10                    | 9.6                            | 9.6                             | 475              | 535 | 3.8                    | 200                |                   |
|                            |                         | 60                     | 0.234                   | 10                    | 9.6                            | 9.6                             | 480              | 570 | 8.7                    | 200                |                   |
| 420                        | 1/16                    | 23.5                   | 0.140                   | 8.5                   | 6.7                            | 17.0                            | 238              | 380 | 6.9                    | 200                |                   |
|                            |                         | 29                     | 0.156                   | 7                     | 6.7                            | 13.7                            | 255              | 380 | 3.0                    | 200                |                   |
|                            |                         | 54.5                   | 0.203                   | 9.5                   | 9.1                            | 10.0                            | 380              | 558 | 5.5                    | 200                |                   |
|                            |                         | 54.5                   | 0.265                   | 8.0                   | 10.9                           | 12.0                            | 338              | 420 | 1.0                    | 200                |                   |
| <u>Nickel Alloys</u>       |                         |                        |                         |                       |                                |                                 |                  |     |                        |                    |                   |
| Huntington 60 <sup>b</sup> | 1/16                    | 36                     | 0.187                   | 8                     | 8.6                            | 14.4                            | 375              | 475 | 7.0                    | None               |                   |
| Huntington 61 <sup>b</sup> | 1/16                    | 30                     | 0.125                   | 9.3                   | 6.2                            | 12.4                            | 340              | 355 | <10                    | 250                |                   |
|                            |                         | 40                     | 0.218                   | 10                    | 9.5                            | 14.4                            | 250              | 520 | 6.9                    | 200                |                   |
| Huntington 82 <sup>b</sup> | 1/16                    | 40                     | 0.125                   | 10                    | 6.4                            | 9.6                             | 540              | 250 | 5                      | 200                |                   |
| <u>Copper Alloys</u>       |                         |                        |                         |                       |                                |                                 |                  |     |                        |                    |                   |
| Linde 63 <sup>c</sup>      | 1/16                    | 30                     | 0.09                    | 9                     | 8.0                            | 16                              | 425              | 410 | <5                     | None               |                   |
| Al (10%) Bronze            | 1/16                    | 30                     | 0.187                   | 10                    | 7.2                            | 14.4                            | 260              | 440 | 5                      | None               |                   |

<sup>a</sup> All deposits made with an oscillation width of about 1 1/2 in. and an average frequency of 50 cpm.

<sup>b</sup> Trademark of International Nickel Co.

<sup>c</sup> Trademark of Linde Div., Union Carbide Corp.

current levels are selected to meet the deposition objectives. Typical deposition rates and welding conditions for a variety of surfacing filler metals are shown in Table 14.

**6.3.3.2** As a rule of thumb, the diameter of the hot wire should not exceed one-half the desired deposit thickness. Accordingly, solid 1/16 in. diameter wire is recommended for applying 1/8 in. to 3/16 in. thick overlays. Solid 3/32 in. diameter wire may be used for applying 3/16 in. thick and heavier deposits. Composite stainless steel wire of 1/16 or 3/32 in. diameter can be used to produce 3/16 in. thick and heavier deposits at a deposition rate approximately 70% of that obtainable with solid wire. Composite surfacing wires can similarly be used if available in 1/16 or 3/32 in. diameters. Flux cored stainless steel or surfacing wires are not recommended because flux interference in the weld puddle precludes satisfactory deposit formation.

#### **6.3.4 Advantages**

**6.3.4.1** Using the plasma-arc welding process for hot-wire surfacing exhibits significant advantages, particularly with high-nickel alloys. The principal advantages are minimum deposit dilution and freedom from voids and inclusions. Practically any metal available as a solid or composite wire can be applied. Because the filler metal melting system is independent of the base metal heating system, dilution is lower and can be better controlled than in other surfacing methods where filler metal melting and arc heat are interrelated. With most metals, single layer deposits can be produced at deposition rates up to 60 lb/h with dilution levels as low as 5 to 10 percent. Surfacing costs are lower for certain metals because thinner deposits which meet the required chemical analysis are possible in a single layer. Good deposit quality can be achieved with little likelihood of voids in the overlap region between adjacent weld passes.

## **7. Process Control**

### **7.1 General**

**7.1.1** The elements necessary for adequate process control of the plasma-arc welding process are similar to the gas tungsten-arc welding process. While such elements as arc voltage or standoff distance are not too critical, other factors, such as orifice-gas mixture and orifice wear are important.

### **7.2 Joint Preparation and Tolerances**

**7.2.1** For most metals with section thicknesses above 1/4 in., a 1/4 in.  $\pm$  1/32 in. root face with a bevel of either 30 or 45 deg is generally acceptable. On some metals, satisfactory square-groove welds can be made in butt joints in thicknesses as great as 3/8 in. with single-pass welding using the keyhole technique. This, however, has to be established by trial for the specific metal being welded.

**7.2.2** Dimensional tolerances are comparable to gas tungsten-arc welding. Sheared edges up to 1/4 in. thick may be satisfactory, but machined joints are preferable. Metal-to-metal fit is preferred, although a gap up to 0.020 in. is permissible on 1/4 in. thick or heavier metal sections. On thinner thicknesses, a

proportionately smaller gap is permitted. Mismatch up to 1/16 in. is permissible on thicknesses 1/4 in. or greater. Proportionately less mismatch to approximately 25% of thickness is permissible on thinner sections.

**7.2.3** For metal thicknesses of 0.030 in. and less, illustrations of tolerances for joint fitup and fixturing are shown in Fig. 25 and Fig. 26. Figure 25 shows the tolerances for joint gap and mismatch as well as the fixture dimensions for hold-down clamps and backup grooves. The tolerances are listed in relation to the metal thickness. Thus, for a square-groove weld in a butt joint, a maximum joint gap of  $0.2 \times t = 0.006$  in. (where  $t = 0.030$  in.) is permitted. This is a very small gap indeed. It decreases to only 0.001 in. for a foil thickness of 0.005 in. The fixturing for such weldments must be tooled with precision.

### 7.3 Considerations for Welding Thin Metal Sections

**7.3.1** It should be noted that the weld puddle in thin metal sections and foils behaves quite differently from the weld puddle in thicker sections. This is due to surface tension, which has become the dominant force. For example, as thinner sections are used, say below 0.030 in., the effect of weight or gravity diminishes until, at 0.015 in., it disappears. The strong effect of surface tension then determines the shape of the molten metal, regardless of the welding position, i.e., whether overhead, vertical, or in the flat (downhand) position.

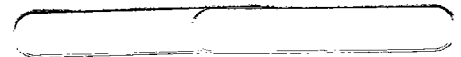
**7.3.2** Good shielding and fixturing are especially important. Weld defects leading to nonrepairable damage and part rejection are largely related to shielding and fixturing due to their effects on the surface tension of melted joint edges. Common oversights in foil welding procedures include:

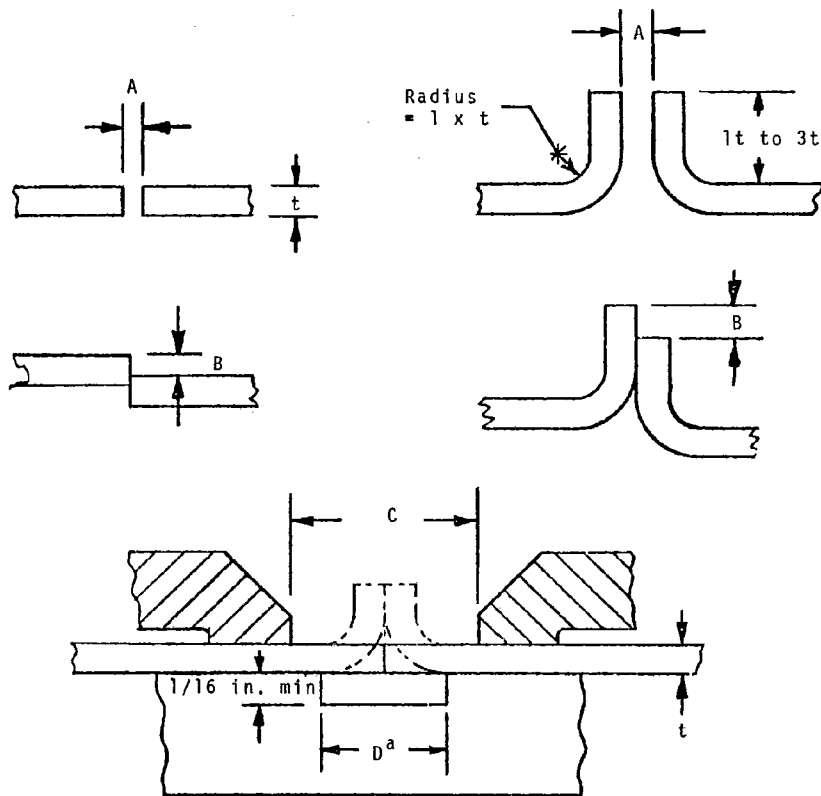
- (1) *Excessive joint gaps* which cannot be bridged by the melted edges.
- (2) *Weld oxidation or base metal oxides* which prevent good wetting and attachment of the molten films.
- (3) *Unbalanced part geometries* (i.e., the free end of a butt joint) which allow puddle contraction in only one direction.
- (4) *Inadequate clamping* which prevents joint warpage during welding.

**7.3.3** The basic requirement in welding thin sections is to make sure, by whatever means possible, that both joint edges are in continuous contact and that both edges melt simultaneously to form a single weld puddle. Separation between the joint edges before or during welding will cause the edges to melt separately and remain separate.

**7.3.4** Increased latitude in butt joint fixturing tolerances can be obtained by modifying the joint, i.e., flanging the edges. The turned-up edges act as preplaced filler metal to fill the gap and assure melt contact with both sides of the joint. They also stiffen the joint edges to minimize warpage from heat buildup during welding.

**7.3.5** Figure 26 shows the fitup and fixturing tolerances for edge joints. Note that on every count, the tolerances are much greater than those for butt joints. Because of this wide tolerance, the edge joint is the easiest and most reliable joint for welding section of foil thickness. Therefore, successful welding of foil-thickness assemblies is greatly assured by converting the joint into some form of edge joint whenever possible.



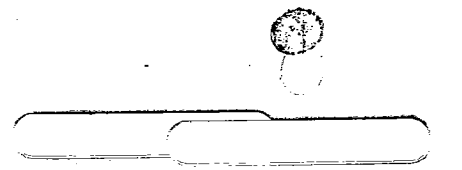
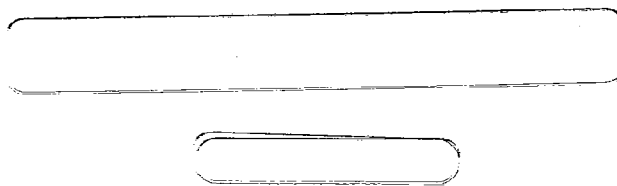


| Butt Joint<br>Type of Weld | Gap<br>"A"<br>max | Mismatch<br>"B"<br>max | Clamp<br>Spacing<br>"C" |     | Backup <sup>a</sup><br>Groove<br>"D" |     |
|----------------------------|-------------------|------------------------|-------------------------|-----|--------------------------------------|-----|
|                            |                   |                        | min                     | max | min                                  | max |
| Square-Groove              | 0.2t              | 0.4t                   | 10t                     | 20t | 4t                                   | 16t |
| Flanged <sup>b</sup>       | 0.6t              | 1t                     | 15t                     | 30t | 4t                                   | 16t |

<sup>a</sup>Gas underbead shielding, either argon or helium, is required.

<sup>b</sup>Edge flange-weld is recommended for butt joints in thicknesses below 0.010 in.

Fig. 25 – Tolerances for butt joints for foil and sheet up to 0.030 in. thick.



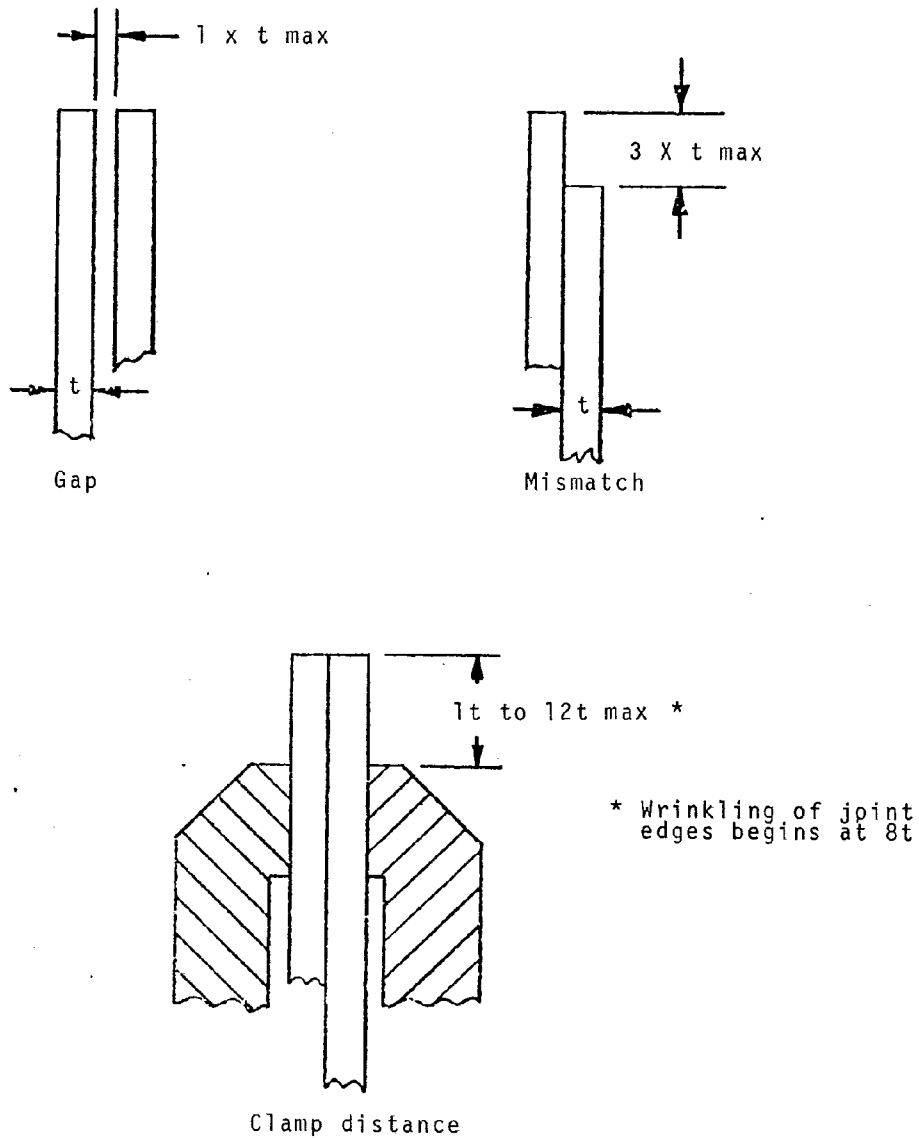


Fig. 26 - Tolerances for edge joints for foil and sheet up to 0.030 in. thick.

### 7.4 Controlling the Operation

**7.4.1** For thin metal sections, weld current has a primary influence over weld quality. Figure 27 illustrates a range of operating currents that will produce acceptable welds.

**7.4.2** Figure 28 indicates, relative to an established optimum, the variations in arc length, travel speed, and percent hydrogen in the shielding gas within which satisfactory welds can still be produced. Available apparatus will easily operate within these limits to yield acceptable joint quality.

**7.4.3** For the high-current keyhole technique for metal thicknesses of 1/16 in. and above, welding conditions are critical and it is recommended that the following tolerances be applied:

- (1) Weld current,  $\pm 5$  A.
- (2) Travel speed,  $\pm 1/8$  in./min.
- (3) Orifice-gas flow rate,  $\pm 1/4$  cfh.
- (4) Shielding-gas flow rate,  $\pm 5$  cfh.
- (5) Torch standoff,  $\pm 1/16$  in.

**7.4.4** For the filler passes where filler metal is added, the control of the welding conditions is not quite so critical as for the root pass using the keyhole technique. The following tolerances for filler passes are recommended:

- (1) Weld current,  $\pm 10$  A.
- (2) Travel speed,  $\pm 1/2$  ipm.
- (3) Orifice-gas flow rate,  $\pm 1/2$  cfh.
- (4) Shielding-gas flow rate,  $\pm 5$  cfh.
- (5) Torch standoff, 1/8 in. to 3/8 in.

**7.4.5** Pure argon is generally used for the keyhole-mode root pass. Either helium or mixtures of helium-argon can be used for filler passes. Where pure helium is specified, high flow rates are required, particularly for shielding. The use of a trailing shield in addition to the normal torch shielding is desirable for making multipass welds on some metals.

### 7.5 Maintenance

**7.5.1** Maintenance is relatively simple. The greatest maintenance problem will be with regard to the orifice nozzle which will elongate with use and will require periodic replacement. The replacement cycle will depend on the current density used and the weld cycle. Replacement will vary from an estimated one hour for high-current, high-duty cycle applications to an indefinite period for low-current, low-duty cycle applications. On equipment that utilizes a pointed tungsten electrode, orifice nozzle life will still depend on the accuracy of centering the tungsten electrode with respect to the orifice.

**7.5.2** The tungsten electrode life will be quite long and will depend on such factors as current density, duty cycle, purity of the orifice gas, and on whether the electrode is water cooled. Under normal operating conditions, tungsten electrode life between dressings should be on the order of 8 to 40 hours.

**7.5.3** Maintenance of equipment such as power supply, controls, meters, etc., will be comparable to the gas tungsten-arc welding process and should be done

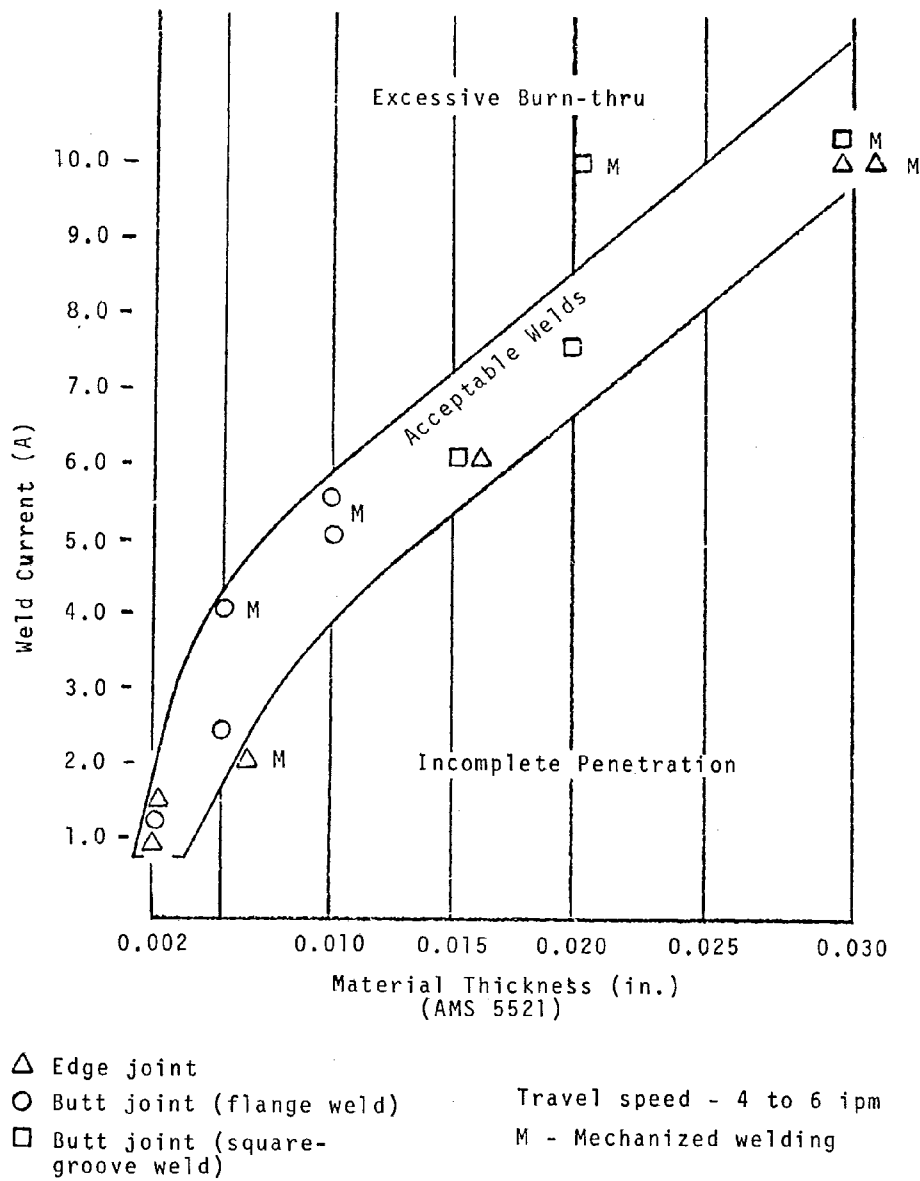


Fig. 27 - Weld current requirements for optimum weld quality.

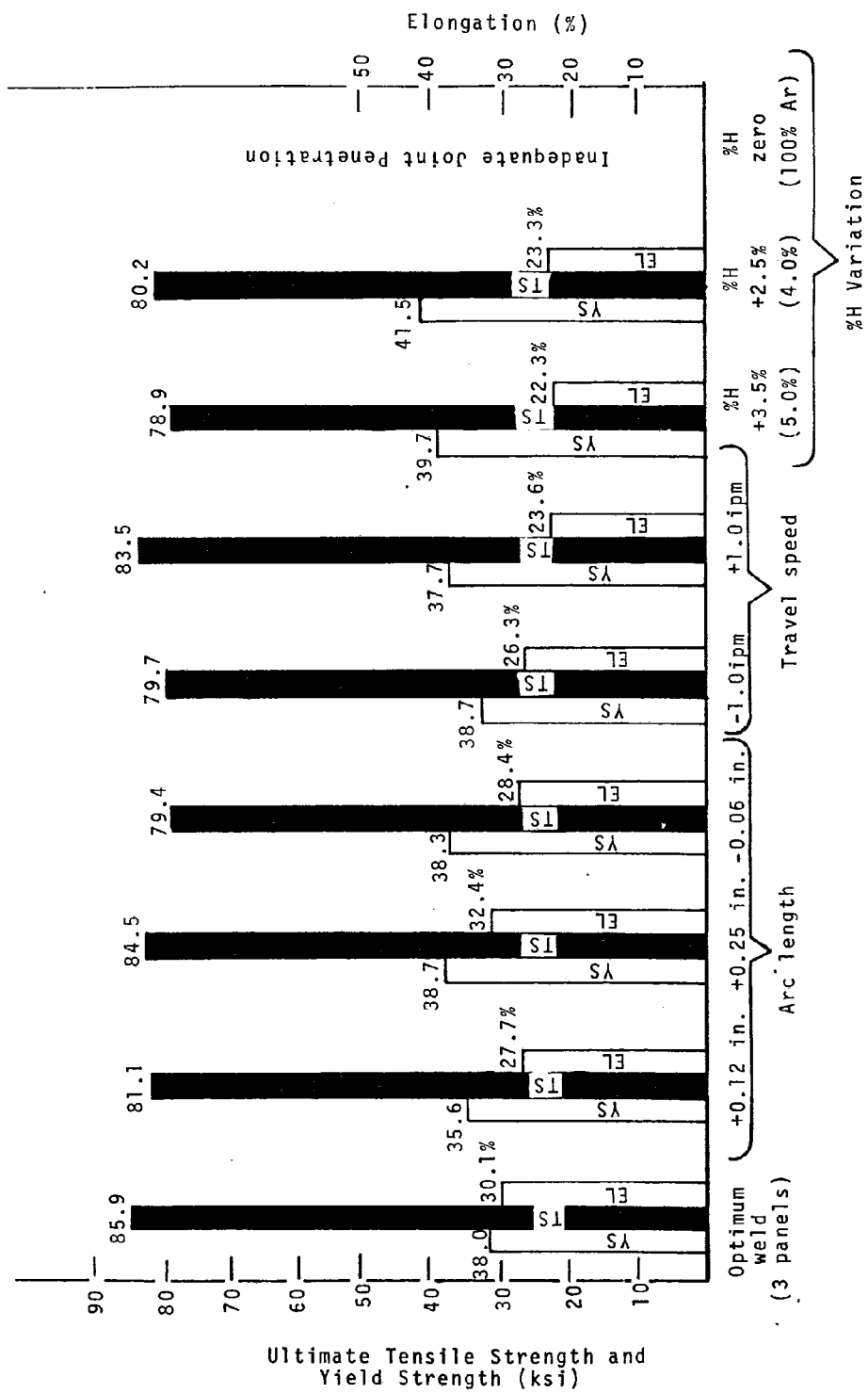


Fig. 28 — Plasma-arc weld mechanical test data, process variation evaluation, 0.015 in. AMS 5521.

periodically. The frequency of maintenance is determined by the specific application and duty cycle.

## 7.6 Inspection and Testing Methods

**7.6.1** Nondestructive testing methods applicable to other welding processes are used for plasma-arc welded joints. Visual, liquid penetrant, and radiographic techniques are adequate to determine weld quality. There are no unique effects exclusive to the process which cannot be evaluated by these methods. Quality levels common to those attainable with the gas tungsten-arc welding process can be anticipated, with the usual considerations being given to cleanliness of parts and material, proper inert-gas shielding at root and face of welds, and metallurgical characteristics of the alloy being joined.

## 7.7 Design Data and Test Results

**7.7.1** Uniaxial tensile strength, bend-test limits, and notch toughness of plasma-arc welds are dependent upon the metallurgical characteristics of the metal welded, in combination with filler metal additions and thermal treatments.

**7.7.2** Because many plasma-arc butt welds up to 1/4 in. are made without filler metal, their properties are unaffected by dissimilar filler metal additions. The low depth-to-width ratio of plasma-arc welds has not indicated advantages in properties, but has indicated reduced defects based upon the quantity of metal melted in the weld.

**7.7.3** The typical properties shown in Fig. 29 illustrate that the uniaxial tensile test properties for Type 310 stainless steel are equivalent to those for the gas tungsten-arc welding process.

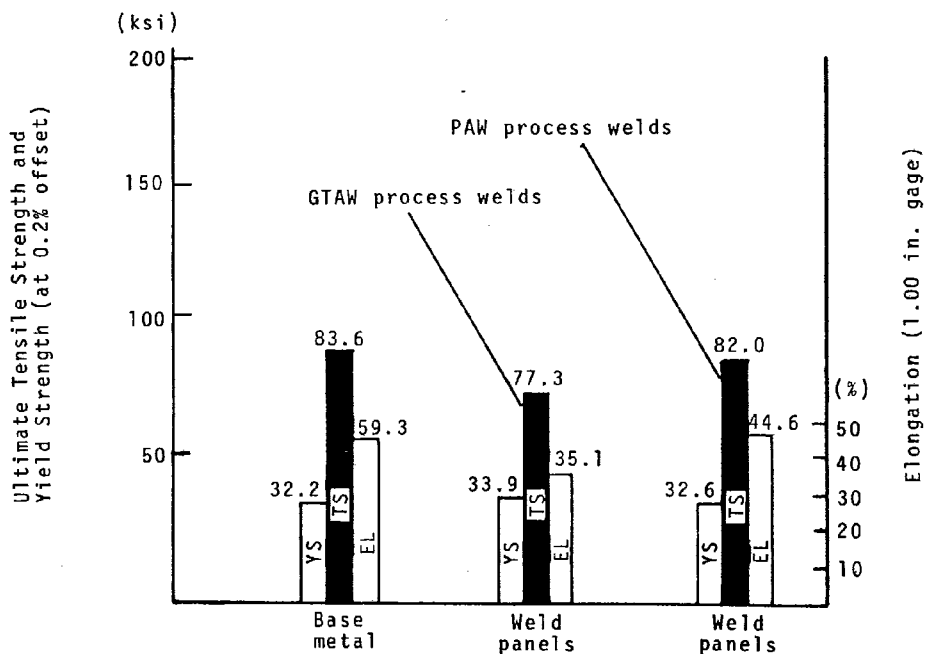


Fig. 29 – Typical average uniaxial tensile properties of low amperage plasma-arc welds for Type 310 stainless steel, 0.030 in. thick.

**7.7.4** Tensile properties of plasma-arc welds in solution-treated and aged 6Al-4V titanium plate 0.25 in. thick exhibit ultimate tensile strengths ranging from 157 to 162 ksi at elongations greater than 6.5% in 1 in. Pre-cracked Charpy impact (PCI) values are significantly higher in titanium weld metal and heat-affected zones than in the base metal for plasma-arc welds. Specimens from several plasma-arc welds evaluated by tensile and PCI testing have been analyzed for interstitial gas content; these analyses all suggest that the keyhole-mode plasma arc actually extracts oxygen from the weld metal. The weld fusion zone in these weldments exhibited oxygen contents from 25 to 40% less than the base metal. The PCI values for weld areas and base metal are in close correlation with gas analyses.

### **7.8 Applicable Specifications**

**7.8.1** The plasma-arc welding process has been individually qualified for several critical government fabrication contracts and accepted as an alternate to the gas tungsten-arc welding process. It will undoubtedly be included when specification revisions are made. The AWS Committee on Welding Symbols has adopted PAW as the process designation for the welding symbols.

**7.8.2** Welds that meet the existing standards for aerospace and nuclear joint quality have been produced by contractors.

**7.8.3** Hot-wire surfacing deposits made with the plasma-arc welding process have been shown to be capable of complying with all the requirements specified in the ASME Boiler and Pressure Vessel Code, Sections III and VIII, and in NAVSHIPS 250-1500-1.

## **8. Training and Qualification of Welders and Welding Operators**

**8.1** Welders and welding operators having previous gas tungsten-arc welding experience are readily trained as plasma-arc welders and welding operators.

**8.2** The major difference in training for plasma-arc welding as compared to gas tungsten-arc welding lies in understanding the significance of the orifice-gas flow and in recognizing the lesser effect of arc voltage as a welding variable. The length and extent of the training will depend on the trainee's former experience, intelligence, attitude, and mechanical aptitude.

**8.3** In manual welding, the welder needs to learn that it is not necessary to maintain a close arc as in other processes, and that the long arc is usually the chief advantage. Along with this, he should be cautioned that amperage decreases as arc length increases, but this, within limits, is not usually a significant factor in the end result. Insofar as torch manipulation is concerned, an inexperienced trainee will generally adapt more rapidly with manual plasma-arc welding than with gas tungsten-arc welding.

**8.4** In mechanized welding, welding operators must be trained to recognize, generate, and maintain keyholing conditions. Torch-side monitoring of keyholing is not adequate until the welding operator has considerable experience. Moreover, for some metals, such as titanium, the required oxidation protection shields at the

torch prevent observing keyholing from the torch side. An underbead viewing system should be arranged whenever possible for maximum reliability.

**8.5** For mechanized welding, the equipment should be qualified to assure that it can be controlled within the tolerances outlined to produce a weld or an overlay of quality comparable to similar work standards for other welding equipment. Testing of the weld should parallel the methods and procedures employed for other welding processes.

**8.6** Specific qualification requirements will be dictated by customer requirements and controlling agency specifications. A typical example is MIL-T-5021C, Tests; Aircraft and Missile Welding Operator's Qualification.

**8.7** Because there are several manufacturers of plasma-arc welding equipment, it is recommended that instructions and assistance be obtained from the equipment supplier in establishing a training program.

## 9. Safety Recommendations

**9.1** For detailed safety information, refer to the manufacturer's instructions and the latest editions of the following publications: Safety in Welding and Cutting, ANSI Z49.1; Recommended Safe Practices for Gas-Shielded Arc Welding, AWS A6.1; and the AWS WELDING HANDBOOK (Sixth Edition), Section I, Chapter 9, "Safe Practices in Welding and Cutting." For mandatory federal safety regulations established by the U.S. Labor Department's Occupational Safety and Health Administration, refer to the latest edition of OSHA Standards, Code of Federal Regulations, Title 29 Part 1910 available from the Superintendent of Documents, U.S. Printing Office, Washington, D.C., 20402.

**9.2** When welding with transferred arc currents up to 5 A, spectacles with side shields or other types of eye protection with a No. 6 filter are recommended. Although face protection is not normally required for this current range, its use depends on personal preference. When welding with transferred arc currents between 5 and 15 A, a full-face light green plastic shield is recommended, in addition to eye protection with a No. 6 filter. At current levels over 15 A, a standard welder's helmet with the proper shade of filter glass for the current being used is required.

**9.3** Wear suitable clothing to protect exposed skin from arc radiation.

**9.4** Turn off welding power before adjusting or replacing electrodes. Use adequate eye protection when observation of a high frequency discharge is required to center the electrode.

**9.5** Turn off the main power switch before opening the control cabinet.

**9.6** Accessory equipment such as wire feeders, arc-voltage heads, oscillators, etc., should be grounded. If they are not grounded, insulation breakdown might cause these units to become electrically "hot" with respect to ground.

**9.7** Use adequate ventilation particularly when welding metals with high copper, lead, zinc, or beryllium contents.

**9.8** If chlorinated solvents have been used to degrease or clean the workpiece, be sure the solvent has been removed before welding. Do not weld near degreasing tanks.

**9.9** Hydrogen is a combustible gas and can be an explosion hazard. Keep open flames away from hydrogen cylinders and hoses. Keep open flames away from the torch when purging. *Never use 1, 2, or 5% argon-oxygen gas mixtures with hydrogen. The mixture is explosive.*

**9.10** Turn off the welding power and shut off any shielding gas supply at the supply source when leaving the work or stopping the work for any appreciable time, or when moving the machine.

**9.11** When a pilot arc is run continuously, use normal precautions to protect against arc flash and heat burns from the effluent.

**9.12** See Appendix for OSHA ear protection requirements.

## **10. Practical Applications**

### **10.1 General**

**10.1.1** The plasma-arc welding process is accepted in the aerospace, hydrospace, nuclear, electronic, shipbuilding, and many other commercial industries. It offers process fabrication latitude and economy while maintaining high quality and reliability. Most metals weldable with the gas tungsten-arc welding process can be satisfactorily welded with the plasma-arc welding process. Accordingly, no exceptions are required in the established gas tungsten-arc acceptance specifications for weldments.

### **10.2 Manual Low-Current Plasma-Arc Welding Applications**

**10.2.1** As previously stated, manual operations do not use the keyhole technique and are therefore similar to gas tungsten-arc welding. However, the welding of very thin metal sections can be accomplished with greater ease and reliability by plasma-arc welding using the nonkeyhole mode. There are exceptions where skilled welding operators have found it advantageous to use the low-current keyhole mode to achieve complete and uniform weld penetration in pipe fabrication. In this regard, the plasma-arc welding process does offer more versatility and is well suited for welding many and varied complicated structures made of thin metal sections.

**10.2.2** A number of proven manual and low-current plasma-arc welding applications are listed below.

- (1) Thin wire mesh screen filters.
- (2) Thin wire butt welds.
- (3) Relay cases.
- (4) Bellows assemblies.
- (5) Exhaust chambers.

- (6) Air ducting.
- (7) Thermal shields.
- (8) Vanes and blades.
- (9) Thin wall pressure vessels.
- (10) Vacuum tube components.
- (11) Microcapsules.
- (12) Thermocouples.
- (13) Filament assemblies.

### **10.3 Mechanized High-Current Plasma-Arc Welding Applications**

**10.3.1** Mechanized high-current plasma-arc welding has proven commercially important in several areas of application due mainly to the keyhole characteristics and the increased welding speeds which result in high quality joints. Many applications are being developed for production. Typical applications are listed below:

- (1) Stainless steel and titanium tubing (longitudinal welds).
- (2) Girth joints in pipe fabrication.
- (3) Missile tankage.
- (4) Turbine engine components.
- (5) Furnace electrodes — compacted reactive metals.
- (6) Tee joints for structural members.

### **10.4 Surfacing with the Plasma-Arc Welding Process**

**10.4.1** Plasma-arc weld surfacing is a fully mechanized operation and shows the greatest economic advantage with high-duty cycle in high-production-type applications. Both metal deposition methods, powder and hot-wire, are highly efficient. The service requirement and the available form of surfacing filler metal determine each specific application.

**10.4.2** Typical applications of powder surfacing are listed below:

- (1) Wear rings.
- (2) Corrosion resisting components.
- (3) Valve cores and faces.
- (4) Bearing surfaces.
- (5) Abrasion- and erosion-resistant surfaces.
- (6) Buildup for worn or corroded surfaces.

**10.4.3** Typical applications of hot-wire surfacing are listed below:

- (1) Heavy wall chemical and nuclear reactor vessels.
- (2) Dished heads and flange rings.
- (3) Cover plates and tube sheets.
- (4) Water-cooled electrodes.

## Appendix: Occupational Noise Exposure\*

"Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown in Table [A] when measured on the A scale of a standard sound level meter at slow response. When noise levels are determined by octave band analysis, the equivalent A-weighted sound level may be determined as shown [in Fig. A].

"When employees are subjected to sound exceeding those listed in Table [A], feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of Table [A], personal protective equipment shall be provided and used to reduce sound levels within the levels of the table.

"If the variations in noise level involve maxima at intervals of one second or less, it is to be considered continuous.

"In all cases where the sound levels exceed the values shown herein, a continuing, effective hearing conservation program shall be administered."

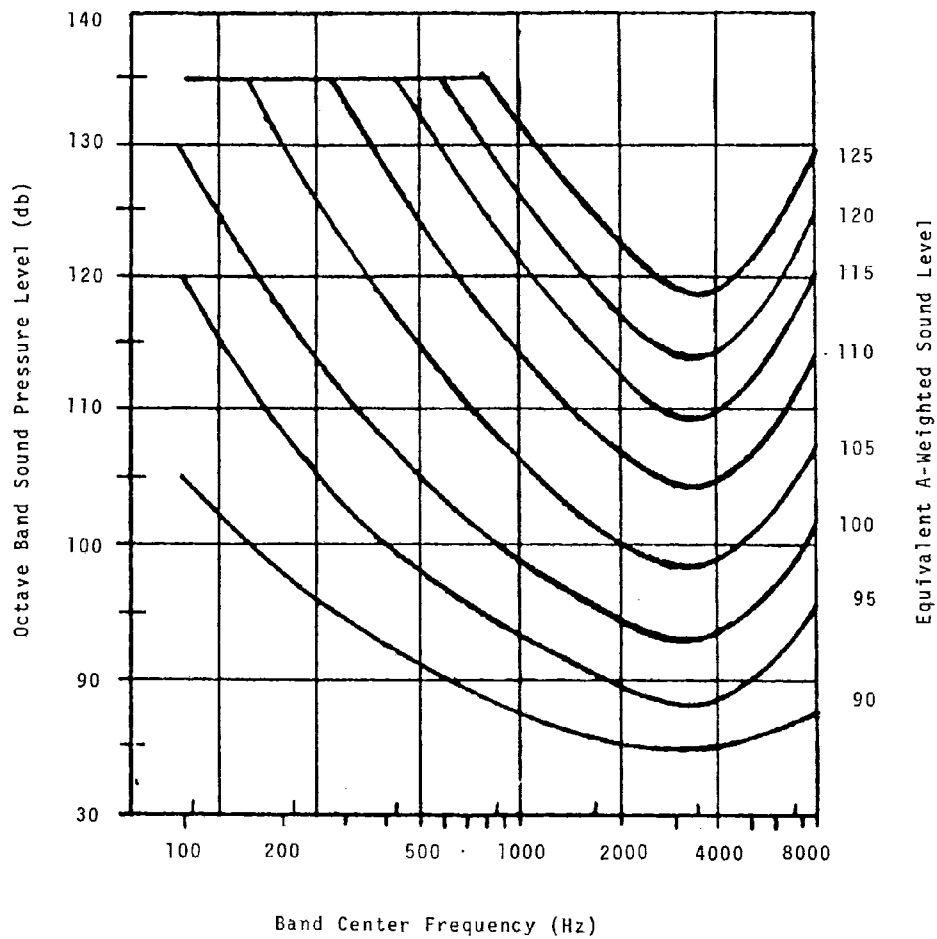
\*OSHA Standards, Code of Federal Regulations, Title 29, Part 1910.

Table A — Permissible noise exposures<sup>a</sup>

| Duration per day, hours | Sound level<br>dBA slow<br>response |
|-------------------------|-------------------------------------|
| 8                       | 90                                  |
| 6                       | 92                                  |
| 4                       | 95                                  |
| 3                       | 97                                  |
| 2                       | 100                                 |
| 1½                      | 102                                 |
| 1                       | 105                                 |
| ½                       | 110                                 |
| ¼ or less               | 115                                 |

<sup>a</sup>When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions:  $C_1/T_1 + C_2/T_2 + \dots + C_n/T_n$  exceeds unity, then, the mixed exposure should be considered to exceed the limit value.  $C_n$  indicates the total time of exposure at a specified noise level, and  $T_n$  indicates the total time of exposure permitted at that level.

Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level.



Equivalent sound level contours. Octave band sound pressure levels may be converted to the equivalent A-weighted sound level by plotting them on this graph and noting the A-weighted sound level corresponding to the point of highest penetration into the sound level contours. This equivalent A-weighted sound level, which may differ from the actual A-weighted sound level of the noise is used to determine exposure limits from Table [A].

Fig. A - Conversion graph—from octave band sound pressure levels to equivalent A-weighted sound levels.

## Bibliography

1. Cooper, G., Palermo, J., and Browning, J.A., "Recent Developments in Plasma Welding," *Welding Journal*, 44 (4), Apr. 1965, pp. 268-276.
2. Filipski, S. P., "Plasma Arc Welding," *Welding Journal*, 43 (11), Nov. 1964, pp. 937-943.
3. Gage, R. M., "Principles of the Modern Arc Torch," *Welding Journal*, 38 (10), Oct. 1959, pp. 959-962.
4. Garrabrant, E. C. and Zuchowski, R. S., "Plasma Arc-Hot Wire Surfacing—A New High Deposition Process," *Welding Journal*, 48 (5), May 1969, pp. 385-395.
5. Gaw, W. D. and Starr, G. L., "Plasma Arc Welding Process Development Program," Technical Report AFML-TR-68, Vols. 1, 2, and 3, March 1969.
6. Gorman, E. F., Skinner, G. M., and Tenni, D. M., "Plasma Needle Arc for Very Low Current Work," *Welding Journal*, 45 (11), Nov. 1966, pp. 899-908.
7. Hackman, R. L., "Plasma Arc Techniques," ASTM Technical Paper No. SP60-135.
8. Hackman, R. L., "Putting Plasma Jets to Work," *The Tool and Manufacturing Engineers*, ASTM, March 1961.
9. Langford, G. J., "Plasma Arc Welding of Structural Titanium Joints," *Welding Journal*, 47 (2), Feb. 1968, pp. 102-113.
10. MacAbee, P. T., Dyar, J. R., and Bratkovich, N. F., "Plasma Arc Welding of Thin Materials," Technical Report AFML-TR-66-177, June 1967.
11. Miller, H. R. and Filipski, S. P., "Automated Plasma Arc Welding for Aerospace and Cryogenic Fabrications," *Welding Journal*, 45 (6), June 1966, pp. 493-501.
12. O'Brien, R. L., "Applications of the Plasma Arc," ASTM Technical Paper No. SP63-56.
13. O'Brien, R. L., "Arc Plasmas for Joining, Cutting, and Surfacing," WRC Bulletin No. 131, July, 1968.
14. "Plasma-Arc Welding," WELDING HANDBOOK, 6th ed., Section 3B, American Welding Society, Miami, 1971, pp. 54.1-54.44.
15. Privoznik, L. J. and Miller, H. R., "Evaluation of Plasma Arc Welding for 120 In. Diameter Rocket Motor Cases," *Welding Journal*, 45 (9), Sept. 1966, pp. 717-725.
16. Zuchowski, R. S. and Garrabrant, E. C., "New Developments in Plasma Arc Welding Surfacing," *Welding Journal*, 43 (1), Jan. 1964, pp. 13-16.