

ANSI/AWS C5.6-89R
An American National Standard

Recommended Practices for Gas Metal Arc Welding



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Keywords — Gas metal arc welding, joint design, arc spot welding, safety training

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An American National Standard

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Recommended Practices for Gas Metal Arc Welding

Prepared by
AWS Committee on Arc Welding and Cutting

Under the Direction of
AWS Technical Activities Committee

Approved by
AWS Board of Directors

Abstract

This standard is a recommended practice on the gas metal arc welding (GMAW) process. This document presents the basic concepts of this process and should enable the reader to obtain a fundamental understanding of this process and its variations, such as short circuit, spray, and pulse modes of metal transfer. It provides the specific technical data which will act as a guide in establishing optimum operation of the process.



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Foreword

(This Foreword is not a part of ANSI/AWS C5.6-89, *Recommended Practices for Gas Metal Arc Welding*, but is included for information purposes only.)

Gas metal arc welding (GMAW) was introduced as a practical fabricating process approximately thirty-eight years ago. In the past ten years, advances have been made in the development of techniques for automatic applications. GMAW applications should continue to expand as fabricators become more familiar with the fundamentals, techniques, and advantages of this welding process.

GMAW welding data was gathered in the late 1970's to yield an authoritative source of sound technical practices for gas metal arc welding. Accordingly, the AWS Committee on Arc Welding and Cutting prepared this recommended practice for gas metal arc welding and published it in 1979. The 1989 edition is the first revision of the 1979 document.

The Committee has developed these guidelines in the hope that they will lead to further development of the gas metal arc process. Comments on this publication will be most welcome. They should be addressed to: Secretary, AWS Arc Welding and Cutting Committee, American Welding Society, 550 N.W. LeJeune Road, P. O. Box 351040, Miami, Florida 33135.

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Recommended Practices for Gas Metal Arc Welding

Note: The U.S. customary units are primary in this publication. However, the approximate equivalent SI values are listed in text and tables to familiarize the reader with the SI system of metric units.

1. Scope

It is intended in this publication to present the basic concepts of the gas metal arc welding (GMAW) process that will enable the reader to obtain a fundamental understanding of the process and its variations.¹ This knowledge, combined with basic information about other welding processes, should be helpful to the reader in the selection of the best welding process for metals to be joined. In addition, the reader will find specific technical data which will be a guide in establishing optimum operation of this process.

Historically, the GMAW process was developed and made commercially available in 1948, although the basic concept was actually introduced in the 1920's. In its early commercial applications, the process was used to weld aluminum with an inert shielding gas, giving rise to the term *MIG* (metal inert gas) which is still in common usage when referring to the process. As time went on, variations were added to the process, among which was the use of active shielding gases, particularly CO₂, for welding certain ferrous materials. This eventually led to the

formally accepted AWS term of *gas metal arc welding* (GMAW) for the process.

Further developments to the process included the following: the short circuiting mode of metal transfer (GMAW-S), a lower heat energy variation of the process that permits welding in all positions and also on sheet metal thicknesses; a method using molding shoes to confine the molten weld metal for vertical welding electrogas welding (EGW); and a method of controlled pulsating current (GMAW-P) to provide a uniform spray droplet metal transfer from the electrode at lower average current levels.

The GMAW process uses either semiautomatic, machine, or automatic equipment and is principally applied in high production welding. Most metals can be welded with this process and may be welded in all positions with the low energy variations of the process. GMAW is an economical process that requires little or no cleaning of the weld metal. Warpage and metal finishing are minimal.

Each of the variations of GMAW provides specific advantages, and standard process equipment is normally designed to permit the use of several of these variations. However, some equipment is designed for one specific mode only. Other variations, such as pulsed current or other processes such as electrogas, require essentially special units which are unique for these variations.

The Committee has prepared these recommended practices as guidelines with the hope that they will serve as an incentive for industry to further develop the GMAW process. The Committee is continuing its activities to provide data for additional materials, designs, and equipment, and these recommended practices will be revised as new information becomes available.

1. *Gas metal arc welding* is defined as an arc welding process that produces coalescence of metals by heating them with an arc between a continuous filler metal electrode and the workpieces. Shielding is obtained entirely from an externally supplied gas.

2. Fundamentals

2.1 Principles of Operation. GMAW is an arc welding process which incorporates the automatic feeding of a continuous, consumable electrode that is shielded by an externally supplied gas. Since the equipment provides for automatic control of the arc, the only manual controls required by the welder for semiautomatic operation are the travel speed, and gun positioning and guidance.

Process control and function are achieved through these the basic elements of equipment (see Figure 1).

- (1) Gun
- (2) Electrode Feed unit
- (3) Power Source

The gun guides the consumable electrode and conducts the electrical current and shielding gas to the workpiece. The electrode feed unit and power source are used in a system that provides automatic regulation of the arc length. The basic combination used to produce this regulation consists of a constant voltage power source (characteristically providing an essentially flat volt-ampere curve) in conjunction with a constant speed electrode feed unit. The arc length self-regulation produced by the constant voltage power source, constant speed electrode feed unit combination is described in detail in 3.2.5. Some GMAW equipment, however, uses a constant current power source (characteristi-

cally providing a drooping volt-ampere curve) plus an arc voltage-controlled electrode feed unit. With this constant current combination, arc voltage changes, caused by a change in the arc length, will initiate a response in the electrode feed unit to either increase or decrease the electrode feed speed to maintain the original arc length setting. In some applications, a constant current power source may be coupled with a constant speed electrode feed unit. This combination will provide only a small degree of automatic self-regulation and can be quite demanding in technique and set-up for semi-automatic welding.

However, some users think this combination affords the range of control over the arc energy that is considered important in coping with the high thermal conductivity of the aluminum base metal.

2.1.1 The following are some advantages of GMAW when compared to SMAW:

- (1) Can be used in all positions with the low energy modes
- (2) Virtually no slag to remove or trap in weld
- (3) Less welder training time than SMAW
- (4) No stub loss
- (5) Adaptable to semiautomatic, machine and automatic welding
- (6) Low hydrogen process
- (7) Faster welding speeds than that used for SMAW

2.1.2 The following are some limitations of GMAW when compared to SMAW:

- (1) The related welding equipment is more complex, more costly, and less portable.
- (2) The shielding gas must be protected from strong winds and air drafts.
- (3) The cooling rates of the completed weld are higher than slag producing processes.
- (4) The welding gun is larger than SMAW electrodes, making it difficult to weld hard-to-reach joint locations.
- (5) The short circuiting welding arc is smaller than the arc produced with the SMAW process. Therefore, the possibility of incomplete fusion exists on thicker weldments due to less heat input and because of arc outages.
- (6) The base metal must be cleaned before welding while SMAW can tolerate some contamination.

2.2 Characteristics. The characteristics of GMAW are best described by the three basic modes of metal transfer which may occur with the process: axial

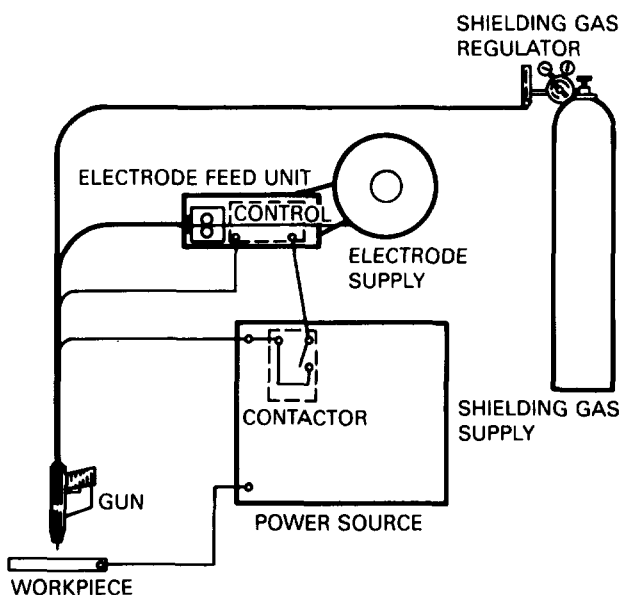


Figure 1 – Basic GMAW Equipment

spray transfer, globular transfer, and short circuiting transfer. Axial spray and globular transfer are associated basically with relatively high arc energy. With the occasional exception of the spray mode in very small diameter electrodes, both axial spray and globular transfer are normally limited to the flat and horizontal welding positions with base metal thickness of not less than 1/8 in. (3.2 mm). Pulsed spray transfer, in which the average energy level is reduced, is another exception (see 2.3.1). Short circuiting transfer is a relatively low energy process generally limited to base metal thicknesses not more than 1/8 in., but is used in all welding positions.

The physics of weld metal transfer are well understood. A combination of forces is responsible for detaching the molten metal from the electrode and propelling it across the arc to the base metal. Two of these forces, gravity and "pinch effect," may be considered in a simple description of the mechanism of transfer and its three basic modes.

Pinch effect is the momentary necking of the liquid drop from the current carrying electrode that occurs as a result of the electromagnetic effects of the current (Figure 2). It is the key to axial spray transfer (see 3.2.6.2). In any conductor, the pinch effect force is proportional to the square of the current flowing through it; i.e., if the current is doubled, the pinch force will be four times as large. This pinch effect can be made large enough to cause the electrode to "neck down" and finally to separate. The molten drop at the end of an electrode is easily pinched off at normal welding currents. Globular transfer is characterized by the predominant effect of the force of gravity.

2.2.1 Axial Spray Transfer (Gas Shield with a Minimum of 90 Percent Argon). In this mode, metal transfer across the arc is in the form of droplets of a size equal to or less than the electrode diameter. The droplets are directed axially in a straight line from the electrode to the weld pool. The arc is very smooth and stable.

The axial spray transfer mode is established at a minimum current level for any given electrode diameter (current density). This current level is generally termed the *transition current* (see Figures 3 and 4). A well defined transition current exists only with gas shield containing a minimum of ninety percent argon. At current levels below the transition current, the drop size increases larger than the diameter of the electrode (see Figures 4 and 5). The arc characteristics are quite unstable in this operating range.

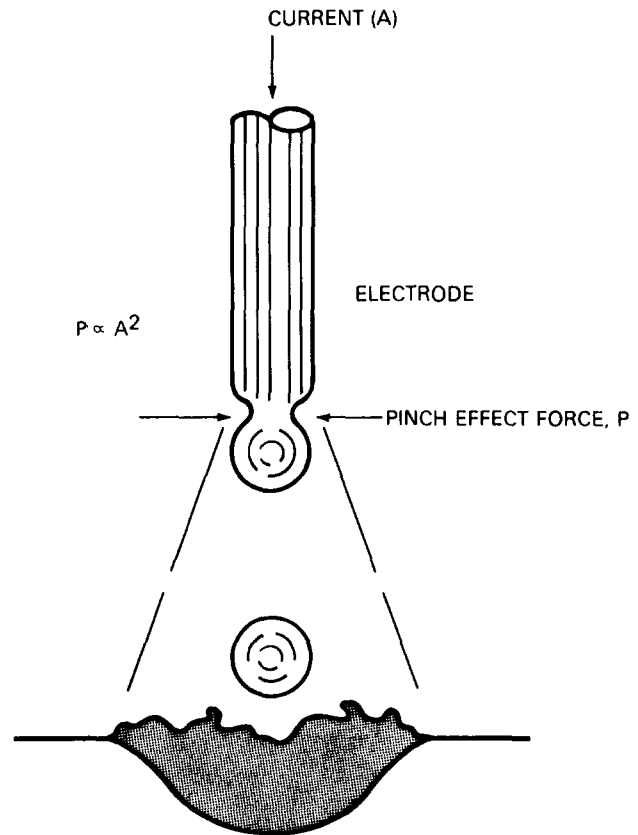


Figure 2 – Illustration of Pinch Effect

2.2.2 Globular Transfer (Gas Shield with CO₂ or Helium). In this mode, metal transfer across the arc is in the form of irregular globules randomly directed across the arc in irregular fashion (see Figure 5), resulting in a considerable amount of spatter. Spatter is minimized when using CO₂ shield by adjusting the welding conditions so that the tip of the electrode is below the surface of the weld pool and within a cavity generated by the force of the arc. The CO₂ arc is generally unstable and characterized by a crackling sound. It results in a weld bead surface that is rough in appearance (ripple effect) in comparison to a bead obtained with axial spray transfer. Since most of the arc energy is directed downward and below the surface of the weld pool, the weld bead cross section exhibits very deep fusion with less wetting at the weld bead extremities than that obtained in the axial spray transfer mode. Relative stability of the CO₂ arc can be established at higher current levels using a buried arc; i.e., wire melts below surface of base metal.

When helium-rich gas mixtures are used, a broader weld bead is produced with a depth of fusion similar to that of argon, but with a more desirable cross section.

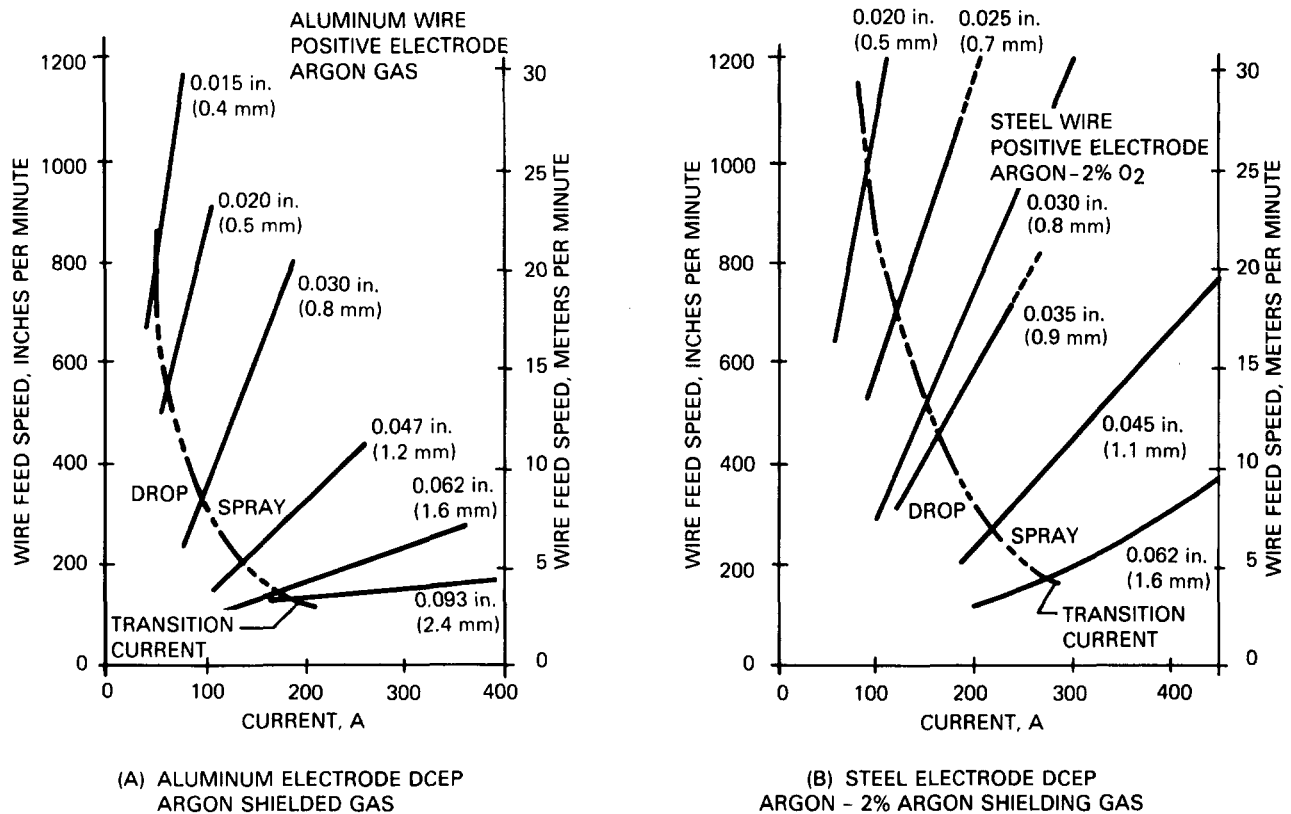


Figure 3 – Melting Rates of Gas Metal Arc Electrodes

2.2.3 Short Circuiting Transfer (GMAW-S). In the short circuiting, low energy mode, all metal transfer occurs when the electrode is in contact with the weld pool. In this mode of metal transfer, the power source characteristics control the relationship between the intermittent establishment of an arc and the short circuiting of the electrode to the work (see Figure 6). Since the heat input is low, the depth of fusion is very shallow, thus, care must be exercised in selecting a procedure and a technique to assure complete fusion when welding thick base metal. However, these characteristics permit welding in all positions. Short circuiting transfer is particularly adaptable to welding sheet metal.

2.3 Variations

2.3.1 Pulsed Current Transfer (GMAW-P). This is a GMAW process variation capable of having good weld pool control at a higher energy level than with short circuit transfer. In this variation, the power source provides two output levels: a steady background level, too low in magnitude to produce any transfer, but able to maintain an arc; and a pulsed high output level which causes melting of

droplets from the electrode which are then transferred across the arc. This pulsed high output (peak) is done at regular intervals, the frequency of which is determined by the particular power source design being used. The net result is to produce a spray arc with average current levels much below the transition current required for a particular diameter and type of electrode (see Figure 7). This brings about increased depth of fusion similar to axial spray transfer, yet improved weld pool control similar to that of short circuit transfer.

GMAW-P is advantageous on thin base metal as well as thick plate and on such base metals as aluminum, stainless steel, carbon steels, nickel steels, and copper alloys.

On thin base metals, its main advantages are reduction of weld spatter and use of larger diameter electrodes. On thicker weldments that cannot be welded with axial spray transfer because of its very fluid weld pool, GMAW-P provides the weld puddle control required. Good welding techniques are very important in order to prevent incomplete fusion defects in the thicker weldments, but it is not as critical as when using the short circuiting mode of metal transfer.

Another use of the GMAW-P mode of transfer is

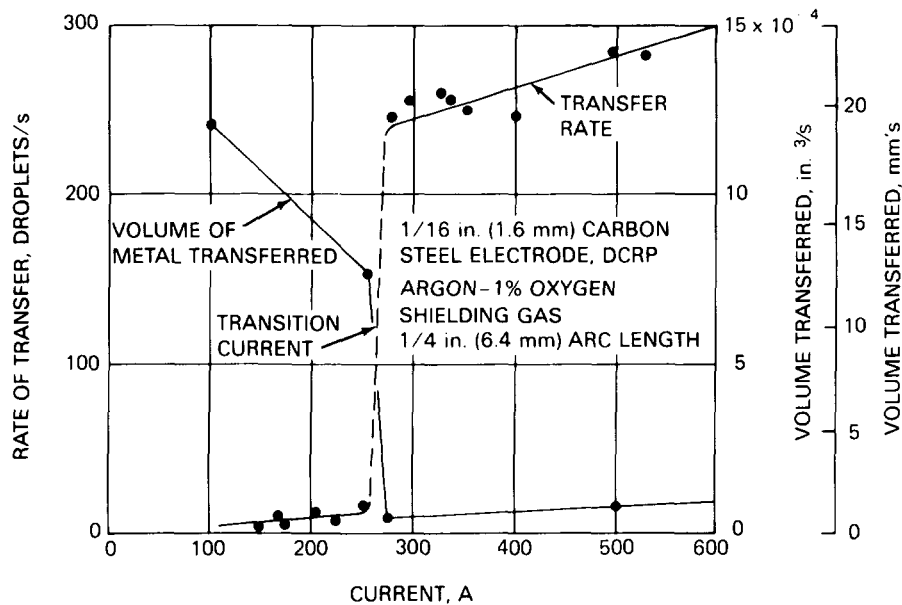


Figure 4 – Variation in Volume and Transfer Rate of Droplets with Welding Current (Steel Electrode)

with copper electrodes alloyed with such deoxidizing elements as silicon and manganese. When used on carbon steel which has a higher melting point than the copper electrodes, the miscible properties of the molten filler metal wire produces a weld (bond) between the base metal and filler metal. Obviously, the strength of the joint will not be the same as a fusion weld, but it is very advantageous on base metals where distortion is a problem. This application is referred to as *gas metal arc braze welding*.

2.3.2 Arc Spot Welding. Adding an arc timer to standard GMAW equipment and special nozzles to the gun is virtually all that is required to provide spot welding capability. The major functional difference between arc spot welding and resistance spot welding is that in arc spot welding the weld begins to form from the outside of one of the joint members rather than at the interface between the two members. This presents both advantages and disadvantages when the processes are compared. Also, GMAW spot welding is not normally considered an all-position welding process. The weld diameter at the faying surface is primarily controlled by the wire feed speed (current), arc time, and the combination of thicknesses being joined. However, the voltage electrode diameter, type of gas shielding, electrode extension, and part fit-up are also very important factors that must be considered to achieve optimum results for a given application.

Precise control of these variables is essential for reproducible results in welding thinner base metals.

2.3.3 Electrode Gas Welding (EGW). This process is an automatic or machine high deposition rate method for welding butt, corner, and T-joints in the vertical position. Electrode gas welding combines the mechanical features of electrode slag welding (ESW) with the GMAW process (see Figure 8). Water-cooled copper, or, in aluminum applications, graphite shoes span the opening between the joint members and forms a cavity for the molten metal. A carriage is mounted on a vertical column to provide both vertical and horizontal movement. Welding

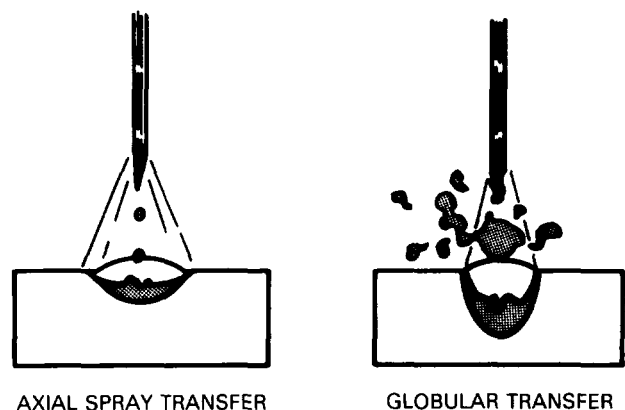


Figure 5 – Weld Metal Transfer Characteristics

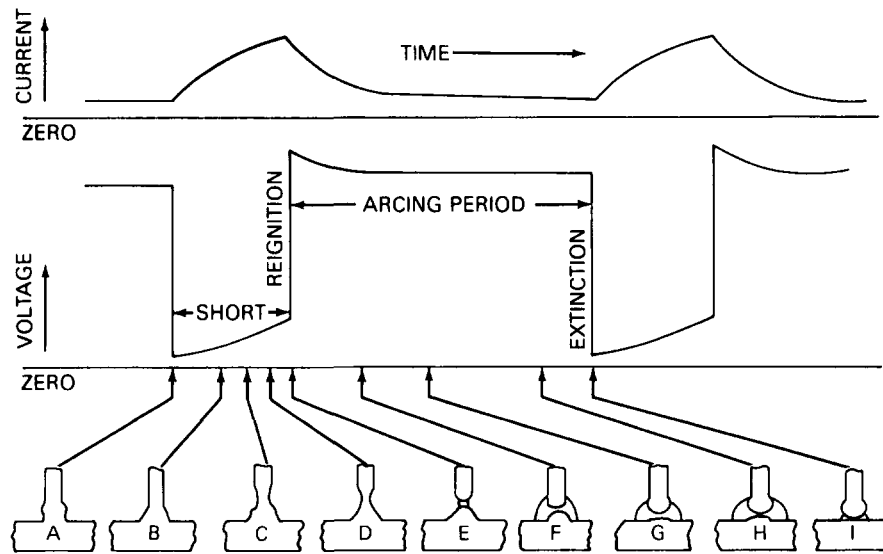


Figure 6 – Oscillograms and Sketches of Short Circuiting Arc Metal Transfer

heat controls and electrode spools are mounted on the carriage.

The carriage and the shoes move vertically upward as welding progresses. The welding head may also be oscillated to provide uniform distribution of heat and weld metal.

This method is capable of welding metal thicknesses of from 1/2 in. (13 mm) to more than 2 in. (50 mm) in thickness in a single pass. Steel deposition rates of 35 to 45 lb (16 to 20 kg) per hour per electrode can be achieved.

3. Equipment

3.1 Introduction. The GMAW process can be used either semiautomatically, machine welding, or automatically. The basic equipment for any GMAW installation consists of the following:

- (1) Welding gun

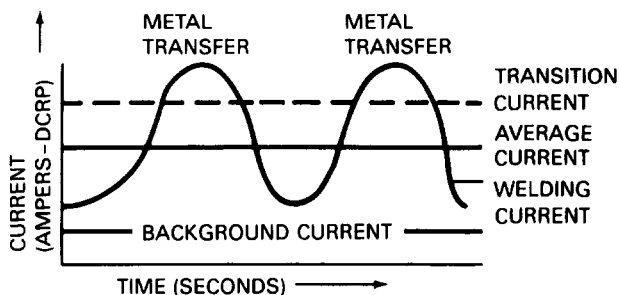


Figure 7 – Time/Ampere Curve for Pulsed Current

- (2) Electrode feed motor and associated gears or drive rolls

- (3) Welding control

- (4) Welding power source

- (5) Regulated supply of shielding gas

- (6) Source of electrode

- (7) Interconnecting cables and hose

Typical semiautomatic and machine welding components are illustrated in Figures 9 and 10.

3.2 Semiautomatic Welding Equipment

3.2.1 Welding Gun and Accessories. The welding gun is used to introduce the electrode and shielding gas into the weld zone and to transmit electrical power to the electrode. Different types of welding guns have been designed to provide maximum efficiency regardless of the application, ranging from heavy duty guns for high current, high production work to light-weight guns for low current or all position welding.

Water or air cooling and curved or straight guns are available for both heavy and lightweight guns. Air cooling permits operation up to 600 amperes at a reduced duty cycle. The same current capacity is available for continuous operation with a water-cooled gun.

The following are basic accessories of these arc welding guns:

- (1) Contact tube (or tip)

- (2) Shielding nozzle

- (3) Electrode conduit and liner

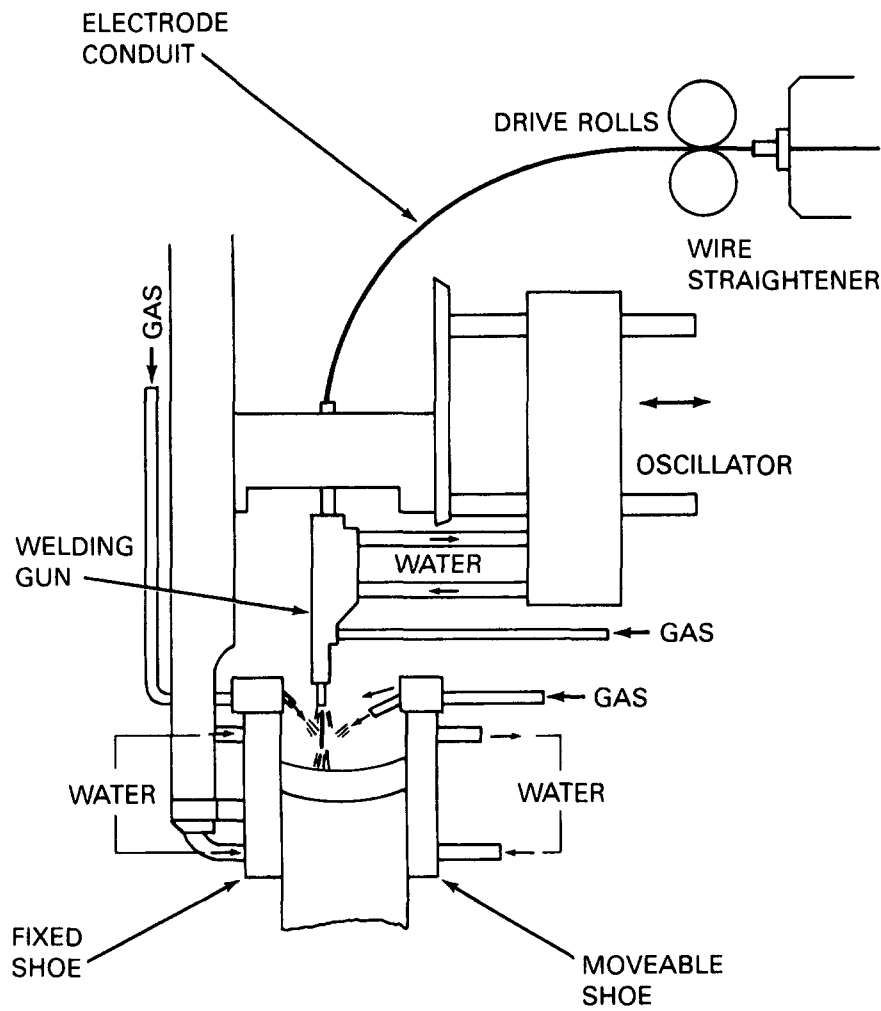


Figure 8 – Schematic of Typical Electrogas Equipment in Weld Area

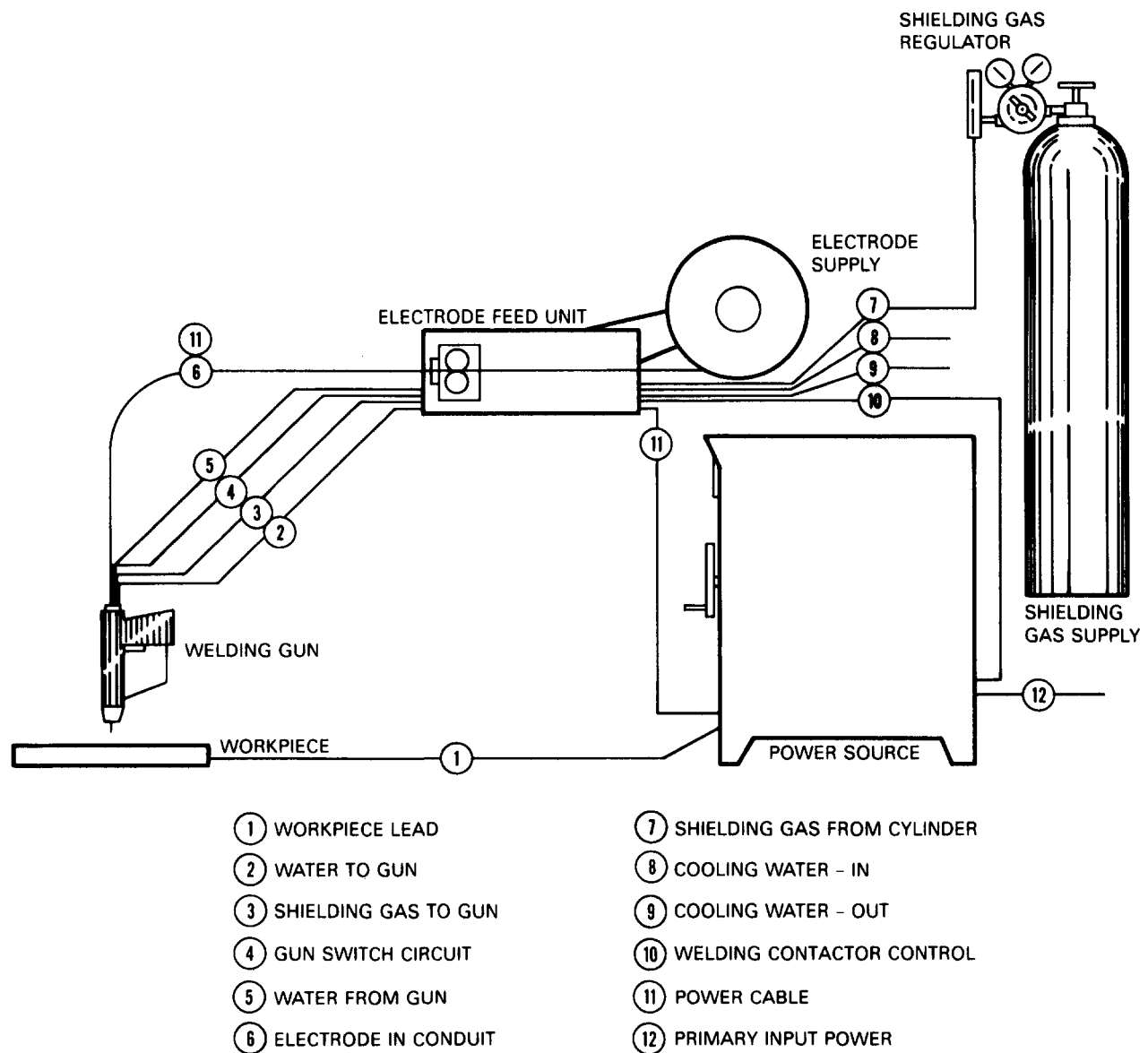


**Figure 9 – Semiautomatic Gas Metal Arc Welding Installation
(Water Cooling of the Torch is Optional)**

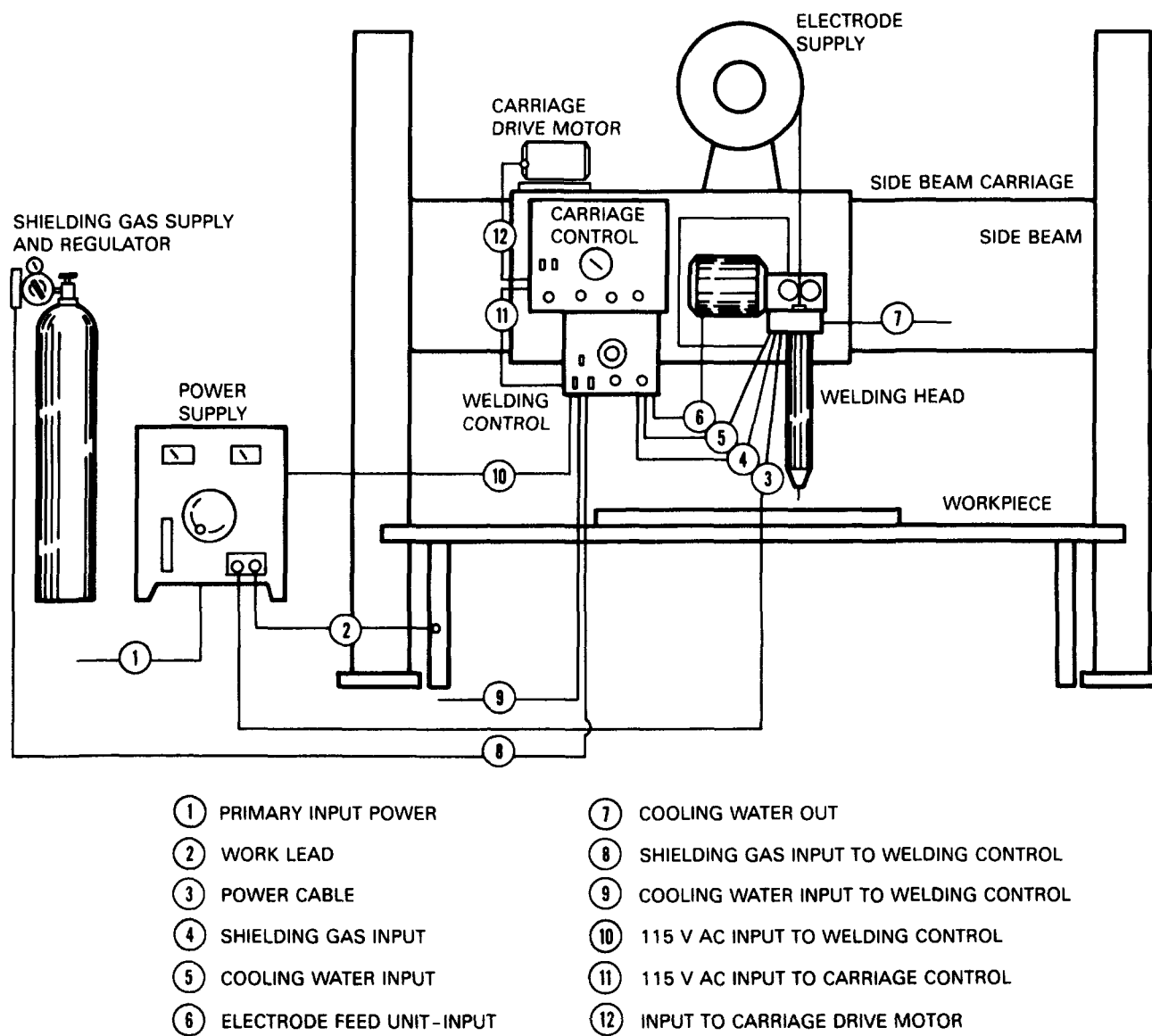


Figure 10 – Machine Gas Metal Arc Welding Installation

- (4) Gas hose
- (5) Water hose
- (6) Power cable
- (7) Control switch

The contact tube, usually made of copper or a copper alloy, is used to transmit welding power to the electrode and to direct the electrode towards the workpiece. The contact tube is connected electrically to the welding power source by the power cable. The inner surface of the contact tube is very important since the electrode must feed easily through this tube and also make good electrical contact. The instruction booklet supplied with every gun will list the correct size contact tube for each electrode size and material. The contact tube must be held firmly by the collet nut (or holding device) and must be centered in the shielding nozzle.

The nozzle directs an even-flowing column of shielding gas into the welding zone. This even flow is very important in providing adequate protection of the molten weld metal from atmospheric contamination. Different size nozzles are available and should be chosen according to the application; i.e., larger nozzles for high current work where the weld pool is large, and smaller nozzles for low current and short circuiting welding. The electrode conduit and liner are connected to a bracket adjacent to the feed rolls on the electrode feed motor. The conduit and liner support, protect and direct the electrode from the feed rolls to the gun and contact tube. Uninterrupted electrode travel is necessary to insure good arc stability. Buckling or kinking of the electrode must be prevented. The electrode will tend to jam anywhere between the drive rolls and the contact tube if not properly supported. The liner may be an integral part of the conduit or supplied separately. In either case, the liner material and inner diameter are important. A steel liner is recommended when using hard electrode materials such as steel and copper, while nylon liners should be used for soft electrode materials such as aluminum and magnesium. Care must be taken not to crimp or excessively bend the conduit, even though its outer surface is usually steel-supported. The instruction manual supplied with each gun will generally list the recommended conduits and liners for each electrode size and material.

The remaining accessories bring the shielding gas, cooling water, and welding power to the gun. These hoses and cables may be connected directly to the source of these facilities or to the welding control. Trailing-gas shields are available and may be required to protect the weld pool during high speed

welding or for some easily-oxidized metals such as titanium.

The basic gun uses an electrode feeder to push the electrode from a remote location through the conduit, a distance of approximately 12 ft (3.7 m). Several other designs are also available, including a unit with a small electrode feed mechanism built into the gun. This system will pull the electrode from a more distant source where an additional drive may also be used to push the electrode into the longer conduit needed. Another variation is the spool-on-gun type in which the electrode feed mechanism and the electrode source are self-contained.

3.2.2 Electrode Feed Motor. The electrode feed motor is usually a direct current type and provides the means for driving the electrode through the gun and to the workpiece. It will have a control circuit which will normally provide for setting the motor speed over a broad range.

The constant speed electrode feed unit is designed to maintain a constant wire feed speed during operation (see 3.2.5). These electrode feed motors are usually shunt-wound or permanent-magnet type. This unit is designed basically for use in conjunction with a constant-voltage (CV) power source.

When a constant current power source is used, a control is provided for variable electrode feed rates during operation. For this application, the electrode feed motor can be a series-wound, shunt-wound, or permanent-magnet type. In this case, the feed motor speed control circuit will respond to arc voltage fluctuations to increase or decrease the wire feed speed to maintain a constant arc length.

3.2.3 Welding Control. The welding control and the electrode feed motor for semiautomatic operation are available in one integrated package (Figure 9). The welding control's main function is to regulate the speed of the electrode feed motor, usually through the use of an electronic governor in the control. The speed of the motor is manually adjustable to provide variable wire feed speed, which, with a constant-voltage (CV) power source, will result in different welding currents. The control regulates the starting and stopping of the electrode feed through a signal received from the gun switch. Also available are electrode feed control features that permit the use of a touch start (the electrode feed is initiated when the electrode touches the workpiece), or a slow run-in (the initial feed rate is slow until the arc is initiated and then increases to that required for

welding). These two features are employed primarily in conjunction with constant current type power supplies and are particularly useful for gas metal arc welding of aluminum.

Shielding gas, water, and welding power are usually delivered to the gun through the control, requiring direct connection of the control to these facilities and the power source. Gas and water flow are regulated to coincide with the weld start and stop by use of solenoids. The control can also sequence the starting and stopping of gas flow and energize the power source contactor. The control may allow some gas to flow before welding starts, as well as a post-flow to protect the weld pool. The control is usually powered by 115 V AC from the power source, but may be powered from an external 115 V source.

3.2.4 Shielding Gas Regulators. A system is required to provide constant shielding gas pressure and flow rate during welding. The regulator reduces the source gas pressure to a constant working pressure regardless of variations at the source. Regulators may be single or dual stage and may have a built-in flowmeter. Dual stage regulators provide a more constant delivery pressure than single stage regulators.

The shielding gas source can be a high pressure cylinder, a liquid-filled cylinder, or a bulk liquid system. Gas mixtures are available in a single cylinder.

Mixing devices may be used for obtaining the correct proportions when two or more gas or liquid sources are used. The size and type of the gas storage source is usually determined by economic considerations based on the usage rate.

3.2.5 Power Source. The welding power source delivers electrical power to the electrode and workpiece to produce the arc. For the vast majority of GMAW applications, direct current electrode positive (dcep) is used; therefore, the positive lead must go to the gun and the negative to the workpiece. The major types of direct current power sources are the engine-generator (rotating) and the transformer-rectifier (static) type. The transformer-rectifier type is usually preferred for in-shop fabrication where a source of either 220 V or 440 V is available; since it has a much faster response time than the engine or motor generator type when the arc condition changes. The engine-generator is used when there is no other available source of electrical energy, such as in the field.

Either type of power source can be used to provide power in the conventional constant current mode or the constant voltage mode. Constant current (drooping characteristics) machines were originally preferred for GMAW because they could also be used for shielded metal arc welding. Constant current machines will maintain a relatively fixed current level during welding, regardless of variations in arc length. These machines are characterized by high open circuit voltages and limited short circuit current levels. Since they supply a virtually constant current output, the arc will maintain a fixed length only if the contact tube-to-workpiece distance remains absolutely constant, with a constant electrode feed rate. In practice, since the contact tube-to-workpiece distance will vary, the arc will then tend to either burn back to the contact tube or "stub" into the workpiece. This can be avoided by using a voltage-controlled electrode feed system with an electrode feed motor whose speed is regulated through a control circuit by an arc-voltage signal. When the voltage (arc-length) increases or decreases, the motor speeds up or slows down to hold the arc length constant. The electrode feed rate is changed automatically by the control system. This type of power source is generally used only for spray transfer arc welding, since the limited duration of the arc in short circuiting transfer makes it impractical to control by voltage regulation (see Figure 6).

As GMAW applications increased, it was found that a constant voltage (CV) machine provided improved operation, particularly with steels. The CV power source, used in conjunction with a constant wire feed speed, maintains a constant voltage during the welding operation. The major reason for selecting CV power is the self-correcting arc length inherent in this system. The CV system compensates for variations in the contact tip-to-workpiece distance, which readily occur during welding, by automatically supplying increased or decreased welding current to maintain the desired arc length. The desired arc length is selected by adjusting the output voltage of the power source; and, normally, no other changes during welding are required. The wire feed speed, which also becomes the current control, is preset by the welder or welding operator prior to welding and can be changed over a considerable range before stubbing to the workpiece or burning-back into the contact tube occurs. Both adjustments require little welder or welding operator skill.

Figure 11 shows the typical static output, volt-ampere characteristics of both constant current and

CV power sources. This figure shows that the constant current power source possesses a drooping volt-ampere curve while the CV source has a relatively flat curve. With either of the two power sources, a small change in the contact tube-to-workpiece distance will cause a change in welding voltage (V) and a resultant change in welding current (A). For the given V shown, a CV power source will produce a large A. This same V causes a smaller A in the constant current power source. The magnitude of A is very important because it determines the change in the electrode melting rate and is the primary mechanism responsible for arc self-correction.

Figure 12 schematically illustrates the self-correction mechanism. As the contact tube-to-workpiece distance increases, the welding voltage and arc length increase and the welding current decreases, as the volt-ampere characteristic predicts. This also decreases the electrode melting rate. Because the electrode is now feeding faster than it is being melted off, the arc will return to approximately the same as the present diameter length. The converse would occur for a decrease in the contact tube-to-workpiece distance.

The large change in current and melt rate associated with CV power can be advantageous, particularly with steel electrodes. Constant current sources are very slow to accomplish this type of correction as the A for any V is too small. If a constant wire feed speed is used with the constant current type power source, the low-conductivity electrode materials have a tendency to stub into the workpiece or burn back into the contact tube.

3.2.6 Power Source Variables. The self-correcting arc property of the CV power source is important in producing stable welding conditions, but there are additional adjustments necessary to produce the best possible condition. These are particularly important for short circuiting welding.

The adjustment of the output voltage is critical. Some degree of slope control of the volt-ampere characteristic may also be desirable, as well as some control of the inductance of the power source. The welder or welding operator should understand the effect of these variables of the welding arc and its stability.

3.2.6.1 Voltage. Arc voltage is the electrical potential between the electrode and the workpiece. This voltage cannot be directly read at the power source because other voltage drops exist throughout

the welding system. The arc voltage varies in the same direction as the arc length; therefore, increasing or decreasing the output voltage of the power source will increase or decrease the arc length.

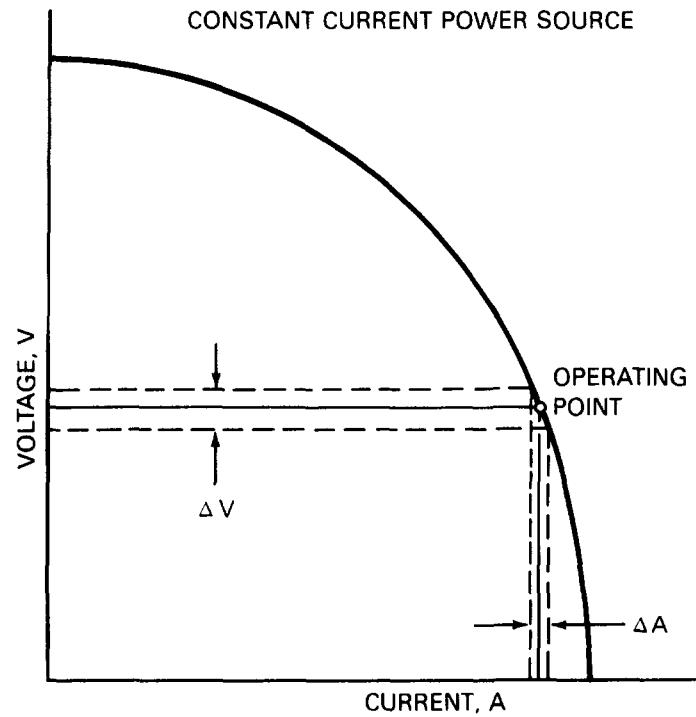
3.2.6.2 Slope. The lower illustration of Figure 11 shows the static volt-ampere slope for a GMAW constant voltage power source. The slant of the curve is referred to as the "slope" of the power source. Slope has the dimensions of resistance since: $\text{Slope} = \text{change in voltage} / \text{change in current} = (\text{volts/ampere}) = \text{ohms}$. This equation states that slope is equivalent to a resistance. However, the slope of a power source is customarily defined as the voltage drop per 100 amperes of current rise, instead of ohms. For example, a 0.03 ohm slope can be restated as a 3 volts per 100 amperes slope.

The open circuit voltage of the power source, as specified by the manufacturer, is measured at its output terminals and is not the total slope of the arc system. Anything which adds resistance to the welding circuit increases slope, and thus, increases the voltage drop at a given welding current. Power cables, poor connections, loose terminals, dirty contacts, etc., add to the slope. Therefore, slope is best measured as close to the arc as possible in a welding circuit. Only two operating points are needed to calculate the slope of a constant-voltage type welding circuit: open circuit voltage and one actual welding point (see Figure 13). The open circuit voltage is the output of the power source found very simply by energizing the weld contactor (turning on the gun switch) and not allowing any electrode feed. The selected welding point may be any stable welding condition.

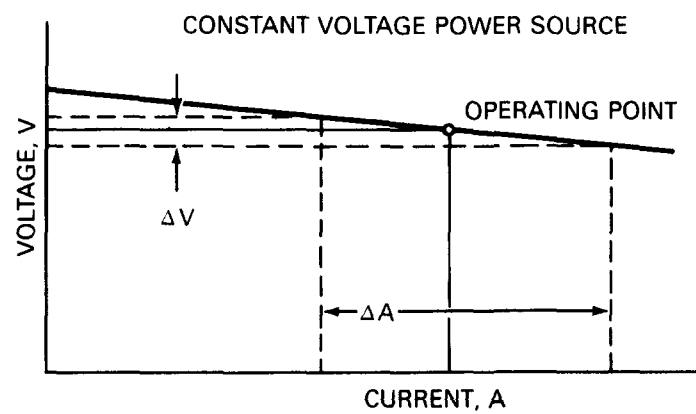
As an example, if the open circuit voltage is 48 volts and the welding condition is 28 volts and 200 amperes, the slope is calculated by determining V and A, as illustrated by Figure 13. In this case, V is 10 volts and A is 100 amperes; the slope is 10 volts per 100 amperes.

Slope in a GMAW system has a major function in short circuiting transfer. The slope controls the magnitude of the short circuit current (zero voltage). This is the current available from the power source on short circuit between the consumable electrode and the workpiece. In GMAW, the separation of molten drops of metal from the electrode is controlled by an electrical phenomenon called the "pinch effect" (see 2.2). Figure 14 illustrates how the pinch effect acts upon an electrode during short circuiting welding.

The short circuit current (with its pinch effect



(A)



(B)

Figure 11 – Static Volt-Ampere Characteristics