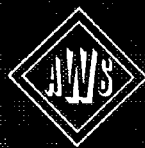


AWS C5.6 89 0784265 0002630 T

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

Recommended Practices for Gas Metal Arc Welding



American Welding Society

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

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

Approved by
American National Standards Institute
August 16, 1989

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.

American Welding Society

550 N.W. LeJeune Road, P.O. Box 351040, Miami, Florida 33135

Statement on Use of AWS Standards

All standards (codes, specifications, recommended practices, methods, classifications, and guides) of the American Welding Society are voluntary consensus standards that have been developed in accordance with the rules of the American National Standards Institute. When AWS standards are either incorporated in, or made part of, documents that are included in federal or state laws and regulations, or the regulations of other governmental bodies, their provisions carry the full legal authority of the statute. In such cases, any changes in those AWS standards must be approved by the governmental body having statutory jurisdiction before they can become a part of those laws and regulations. In all cases, these standards carry the full legal authority of the contract or other document that invokes AWS standards. Where this contractual relationship exists, changes in or deviations from requirements of an AWS standard must be by agreement between the contracting parties.

International Standard Book Number: 0-87171-301-2

American Welding Society, 550 N.W. LeJeune Road, P.O. Box 351040, Miami, Florida 33135

© 1989 by American Welding Society. All rights reserved
Printed in the United States of America

Note: The primary purpose of AWS is to serve and benefit its members. To this end, AWS provides a forum for the exchange, consideration, and discussion of ideas and proposals that are relevant to the welding industry and the consensus of which forms the basis for these standards. By providing such a forum, AWS does not assume any duties to which a user of these standards may be required to adhere. By publishing this standard, the American Welding Society does not insure anyone using the information it contains against any liability arising from that use. Publication of a standard by the American Welding Society does not carry with it any right to make, use, or sell any patented items. Users of the information in this standard should make an independent investigation of the validity of that information for their particular use and the patent status of any item referred to herein.

This standard is subject to revision at any time by the AWS Arc Welding and Cutting Committee. It must be reviewed every five years and if not revised, it must be either reapproved or withdrawn. Comments (recommendations, additions, or deletions) and any pertinent data that may be of use in improving this standard are requested and should be addressed to AWS Headquarters. Such comments will receive careful considerations by the AWS Arc Welding and Cutting Committee, and the author of the comments will be informed of the committee's response to the comments. Guests are invited to attend all meetings of the AWS Arc Welding and Cutting Committee to express their comments verbally. Procedures for appeal of an adverse decision concerning all such comments are provided in the Rules of Operation of the Technical Activities Committee. A copy of these Rules can be obtained from the American Welding Society, 550 N.W. LeJeune Road, P.O. Box 351040, Miami, Florida 33135.

Personnel

AWS Committee on Arc Welding and Cutting

<i>E.R. Bohnart, Chairman</i>	Miller Electric Mfg. Company
<i>J.R. Hannahs, 1st V. Chairman</i>	Midmark Corporation
<i>B.L. Shultz, 2nd V. Chairman</i>	Taylor-Winfield Corporation
<i>W.A. Dierschow, Secretary</i>	American Welding Society
<i>D.R. Amos</i>	Westinghouse Turbine Plant
<i>W.L. Ballis</i>	Columbia Gas Distribution Company
<i>K.E. Banks</i>	Teledyne Mckay
<i>R.L. Bennett</i>	Thermal Dynamics Corporation
<i>L.A. Colarossi**</i>	Consultant
<i>J.R. Condra</i>	E.I. DuPont de Nemours & Company
<i>N.A. Freytag</i>	The Budd Company
<i>R.H. Frost</i>	Colorado School of Mines
<i>R.T. Hemzacek*</i>	Argonne National Laboratory
<i>G.K. Hicken</i>	Sandia National Laboratory
<i>J.E. Hinkel</i>	Lincoln Electric Company
<i>D.B. Holliday</i>	Westinghouse Electric Corporation
<i>L.C. Northard**</i>	Tennessee Valley Authority
<i>N.E. Larson</i>	Union Carbide Corporation
<i>E.R. Pierre</i>	Liquid Air Corporation
<i>L.J. Privoznik</i>	Westinghouse Electric Corporation
<i>J.S. Sayre</i>	Consultant
<i>L.R. Soisson</i>	Arcair Company
<i>M.D. Stepath*</i>	Arcair Company
<i>E.P. Vilkas</i>	Astro Arc Company
<i>G.K. Willecke**</i>	Miller Electric Mfg. Company

Subcommittee on Gas Metal Arc Welding

<i>W.L. Ballis, Chairman</i>	Columbia Gas Distribution Company
<i>E.R. Bohnart</i>	Miller Electric Mfg. Company
<i>D.A. Fink</i>	Lincoln Electric Company
<i>N.A. Freytag</i>	The Budd Company
<i>E.H. Gray</i>	U.S. Nuclear Regulatory Commission
<i>L. Helleman</i>	Cincinnati Milacron
<i>D.B. Holliday</i>	Westinghouse Electric Corporation
<i>G.R. Rothchild*</i>	Consultant
<i>W.G. Woolery</i>	Illinois Power Company

*Advisor

**Deceased

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.

Table of Contents

	Page No.
<i>Personnel</i>	iii
<i>Foreword</i>	iv
<i>List of Tables</i>	vii
<i>List of Figures</i>	viii
 1. <i>Scope</i>	 1
2. <i>Fundamentals</i>	2
2.1 Principals of Operation	2
2.2 Characteristics	2
2.3 Variations	4
3. <i>Equipment</i>	6
3.1 Introduction	6
3.2 Semiautomatic Welding Equipment	6
3.3 Automatic Welding Equipment	16
4. <i>Process Requirements and Application</i>	17
4.1 Shielding Gas	17
4.2 Electrodes	19
4.3 Selection of Process Variables	19
4.4 Welding Variables	22
5. <i>General Joint Design</i>	25
6. <i>Spot Welding</i>	25
6.1 Equipment Operation	33
6.2 Effect of Process Variables on Weld Characteristics	33
6.3 Joint Design	33
6.4 Tension-Shear Test	43
7. <i>Inspection and Weld Quality</i>	43
7.1 Introduction	43
7.2 Potential Problems	43
7.3 Weld Discontinuities	44
8. <i>Training</i>	49
8.1 Introductory Training Program on Steel	50
8.2 Welding Nonferrous Metals	50
8.3 GMAW Course for Steel Pipe	50
8.4 GMAW Equipment Maintenance and Trouble-Shooting Course	51

9. <i>Qualification</i>	51
9.1 Introduction	51
9.2 General	51
9.3 Procedure Qualification	52
9.4 Variables	52
9.5 Types of Tests	52
10. <i>Safe Practices</i>	60
10.1 Scope	60
10.2 Discussion of Potential Hazards	60
10.3 Gases	63
10.4 Radiation	64
10.5 Electric Shock	64
10.6 Noise	64
10.7 Other Factors	64

List of Tables

Table	Page No.
1 — Typical Currents (Short Circuit) for Metal Transfer in the Short Circuiting Mode (Power Source-Static Characteristics)	16
2 — Shielding Gases and Gas Mixtures for GMAW	20
3 — Selection of Gases for GMAW with Spray Transfer	21
4 — Selection of Gases for GMAW with Short Circuiting Transfer	22
5 — Recommended Filler Metals for GMAW	23
6 — How Changes in Welding Variables Affect Weld	25
7 — Strength Equivalents (Effective Throat Depth) by Process for Fillet Welds	26
8 — GMAW Spot Welding of Plain Carbon Steel in the Flat Position CO ₂ Shielding Gas — 3/16 in. (4.8 mm) Diameter Nugget	39
9 — GMAW Spot Welding of Plain Carbon Steel in the Flat Position CO ₂ Shielding Gas — 1/4 in. (6.4 mm) Diameter Nugget	40
10 — GMAW Spot and Plug Welds on Aluminum Argon Shielding Gas — 1/16 in. (1.6 mm) Diameter Electrode	41
11 — Summary of Operating Conditions for GMAW Spot Welding of Various Gauges of AZ31B (Magnesium) sheet with AZ61A Electrode	42
12 — GMAW Spot Welding of Stainless Steel to Plain Carbon Steel in the Flat Position	43

List of Figures

Figure	Page No.
1 — Basic GMAW Equipment	2
2 — Illustration of Pinch Effect	3
3 — Melting Rates of Gas Metal Arc Electrodes	4
4 — Variation in Volume and Transfer Rate of Droplets with Welding Current	5
5 — Weld Metal Transfer Characteristics	5
6 — Oscillograms and Sketches of Short Circuiting Arc Metal Transfer	6
7 — Time/Ampere Curve for Pulsed Current	6
8 — Schematic of Typical Electrode Gas Equipment in Weld Area	7
9 — Semiautomatic Gas Metal Arc Welding Installation (Water Cooling of the Torch is Optional)	8
10 — Machine Gas Metal Arc Welding Installation	9
11 — Static Volt-Ampere Characteristics	13
12 — Automatic Regulation of Arc Length in the GMAW Process with a Conventional Power Supply	14
13 — Calculation of the Slope for a Power Source	15
14 — Illustration of Pinch Effect During Short Circuiting Transfer	15
15 — Effect of Changing Slope	16
16 — Change in Rate of Current Rise Due to Added Inductance	16
17 — Bead Cross Section and Depth of Fusion (Penetration) Patterns with Various Shielding Gases	18
18 — Relative Effect of O ₂ Versus CO ₂ Additions to the Argon Shield	19
19 — Electrode Extension	23
20 — Typical Melting Rates for Plain Carbon Steel	26
21 — Typical Welding Currents Versus Wire Feed Speeds for Carbon Steel Electrodes	27
22 — Typical Melting Rates for Aluminum Electrodes	27
23 — Welding Currents Versus Wire Feed Speed for ER4043 Aluminum Electrodes	28
24 — Welding Currents Versus Wire Feed Speed for ER5356 Aluminum Electrodes	28
25 — Typical Melting Rates for 300 Series Stainless Steel Electrodes	29
26 — Typical Welding Currents Versus Wire Feed Speeds for 300 Series Stainless Steel Electrodes	29
27 — Typical Melting Rates for ECu Copper Electrodes	30
28 — Welding Currents Versus Wire Feed Speed for ECu Copper Electrodes	30
29 — Typical Melting Rates for ECuSi-A Copper Electrodes	31
30 — Welding Currents Versus Wire Feed Speed for ECuSi-A Copper Electrodes	31
31 — Typical Currents Versus Wire Feed Speed for Magnesium Electrodes	32
32 — Optimum Short Circuit Transfer for Plain Carbon Steel Electrodes	32
33 — Optimum Short Circuit Transfer for Carbon Steel Electrodes	33
34 — Typical Weld Joint Design for GMAW (Steel)	34
35 — Fillet Weld — Effective Throats	38
36 — Types of Joints for GMAW Spot Welding	38
37 — Tension — Shear Test Specimen Dimensions	38
38 — Undercutting at the Toe of the Weld	44
39 — Porosity Due to Inadequate Shielding Gas Coverage	45
40 — Porosity Due to Excessive Voltage	46
41 — Incomplete Fusion Due to Narrow Groove Preparation (5083 Aluminum Plate and ER5183 Filler Metal)	46
42 — Incomplete Root Penetration Due to Inadequate Welding Current	46
43 — Weld Metal Cracking Due to Excessive Depth-to-Width Ratio	47

44 — Weld Metal Cracking in Crater at End of Weld	47
45 — Incomplete Fusion Due to Excessive Travel Speed	48
46 — Weld Bead Waviness	49
47 — Sagging of Weld Bead Due to Position of Welding	49
48 — Overlap of Weld Bead Due to Incorrect Voltage	50
49 — Humping of Weld Metal Due to Excessive Travel Speed	50
50 — Example of Workmanship Samples	53
51 — Example of Workmanship Sample	54
52 — Workmanship Specimens	55
53 — Penetration of Filler Weld Break Test Specimen	56
54 — Methods for Facilitating Fillet Weld Fracture	56
55 — Longitudinal Fillet Weld Shearing Specimen After Welding	56
56 — Transverse Fillet Weld Shearing Specimen	57
57 — Longitudinal Fillet Weld Specimen After Machining	57
58 — Fillet Weld-Soundness Test Specimen	57
59 — Reduced-Section Tension Specimen (Plate)	58
60 — Reduced-Section Tension Specimen (Pipe)	58
61 — Face- and Root-Bend Specimen (Plate)	59
62 — Face- and Root-Bend Specimen (Pipe)	59
63 — Side-Bend Specimen	60
64 — Position of Fillet Welds	61
65 — Position of Groove Welds	62

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

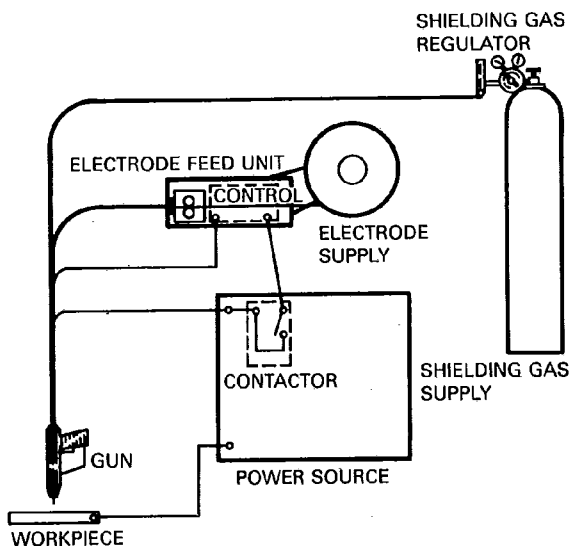


Figure 1 – Basic GMAW Equipment

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.

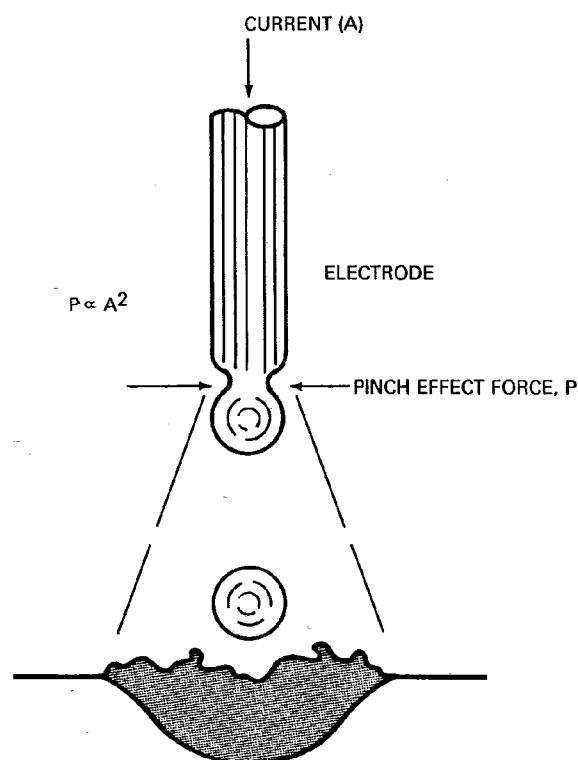


Figure 2 - Illustration of Pinch Effect

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.

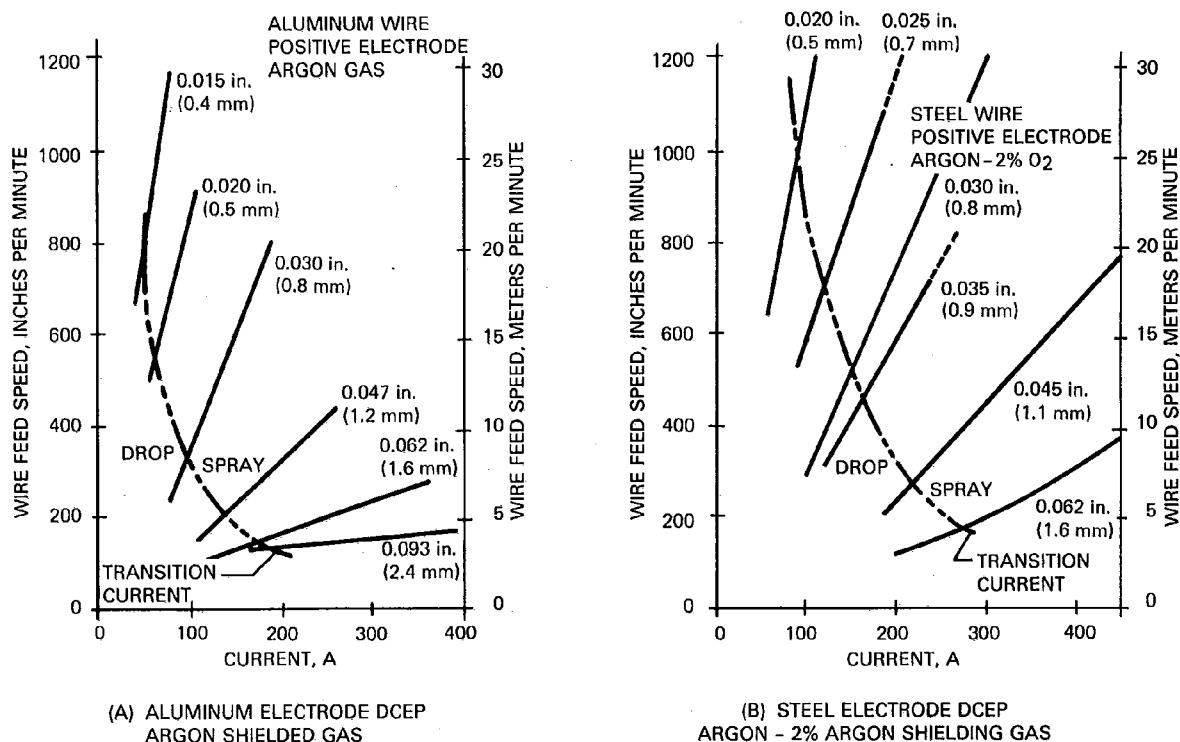


Figure 3 - Melting Rates of Gas Metal Arc Electrodes

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

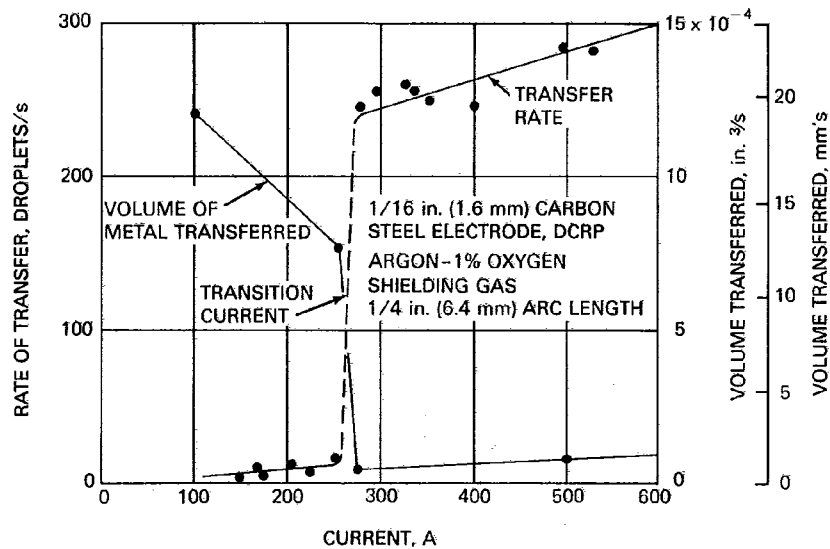


Figure 4 – Variation in Volume and Transfer Rate of Droplets with Welding Current (Steel Electrode)

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

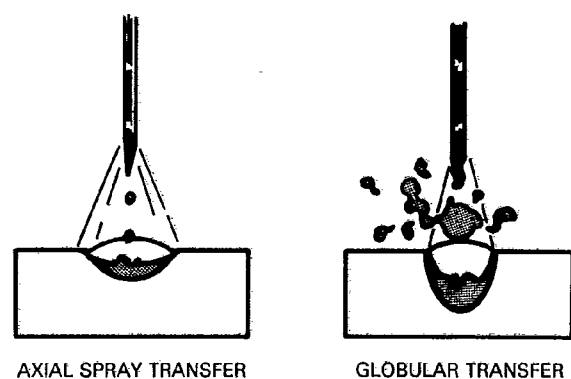


Figure 5 – Weld Metal Transfer Characteristics

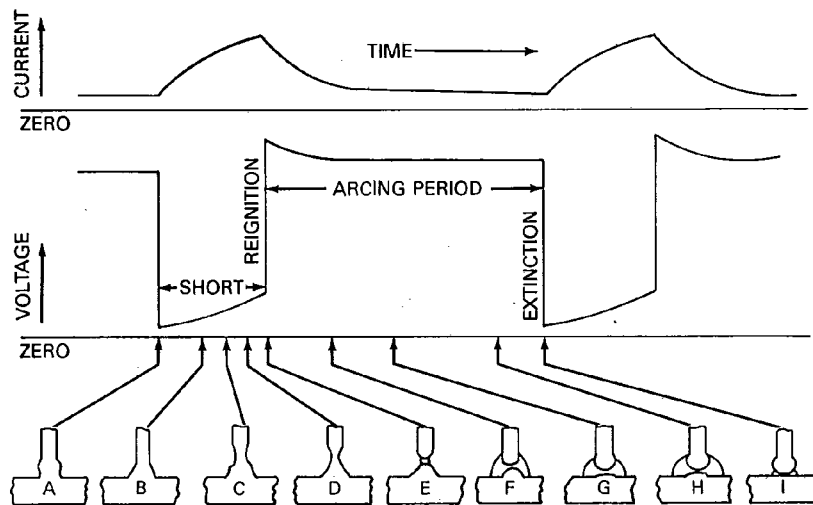


Figure 6 – Oscillograms and Sketches of Short Circuiting Arc Metal Transfer

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

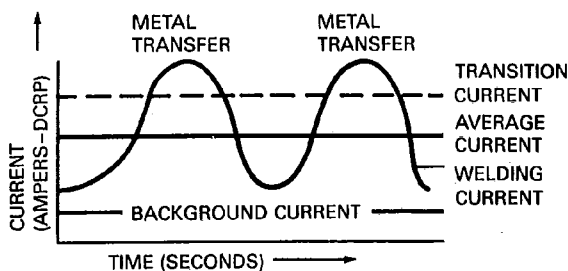


Figure 7 – Time/Ampere Curve for Pulsed Current

- (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

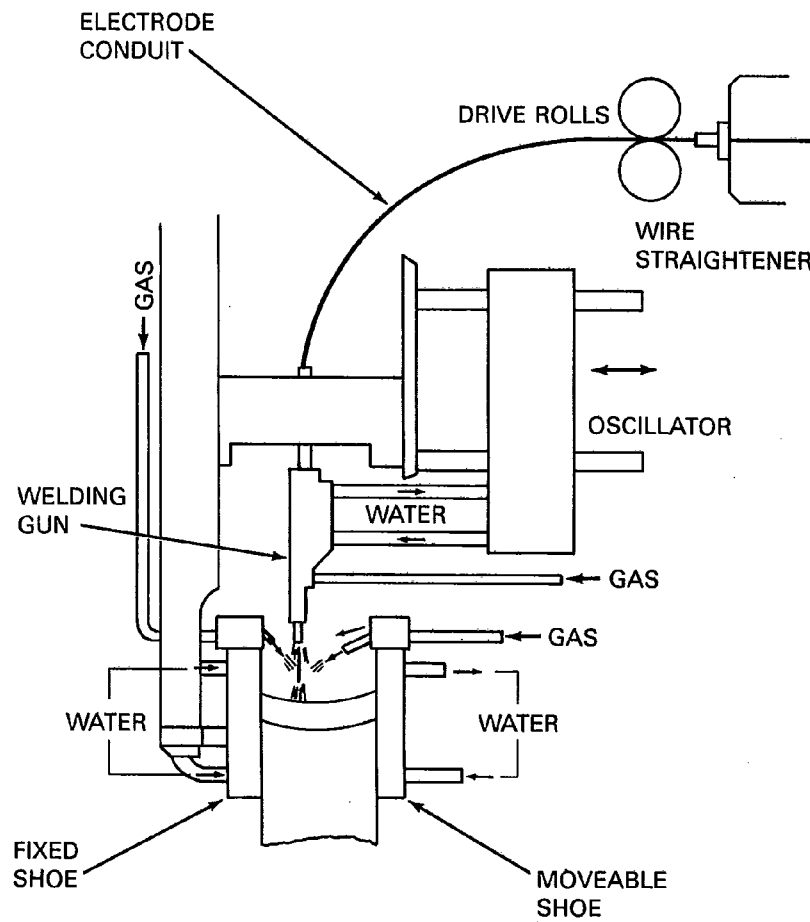
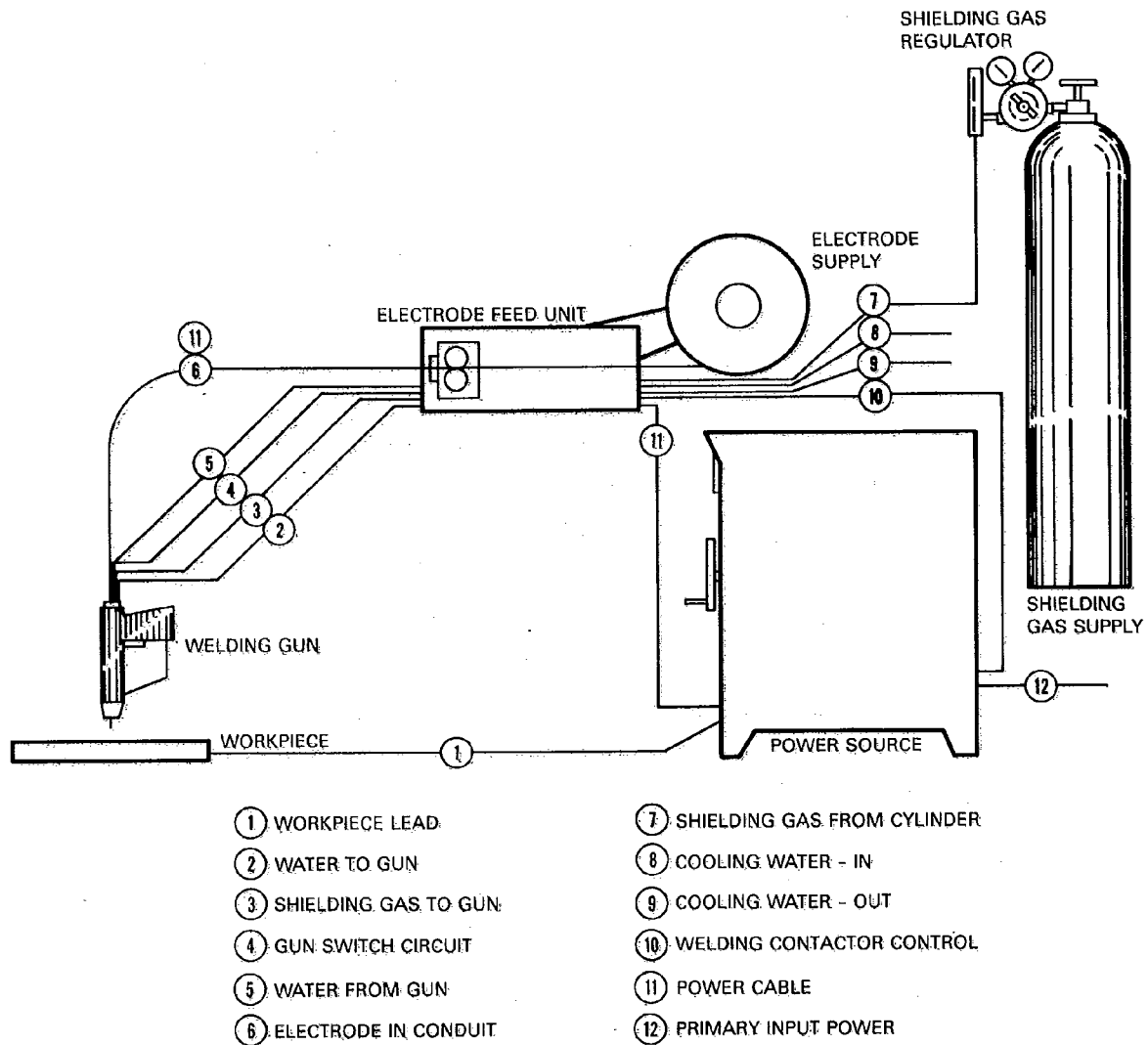


Figure 8 – Schematic of Typical ElectroGas Equipment in Weld Area



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

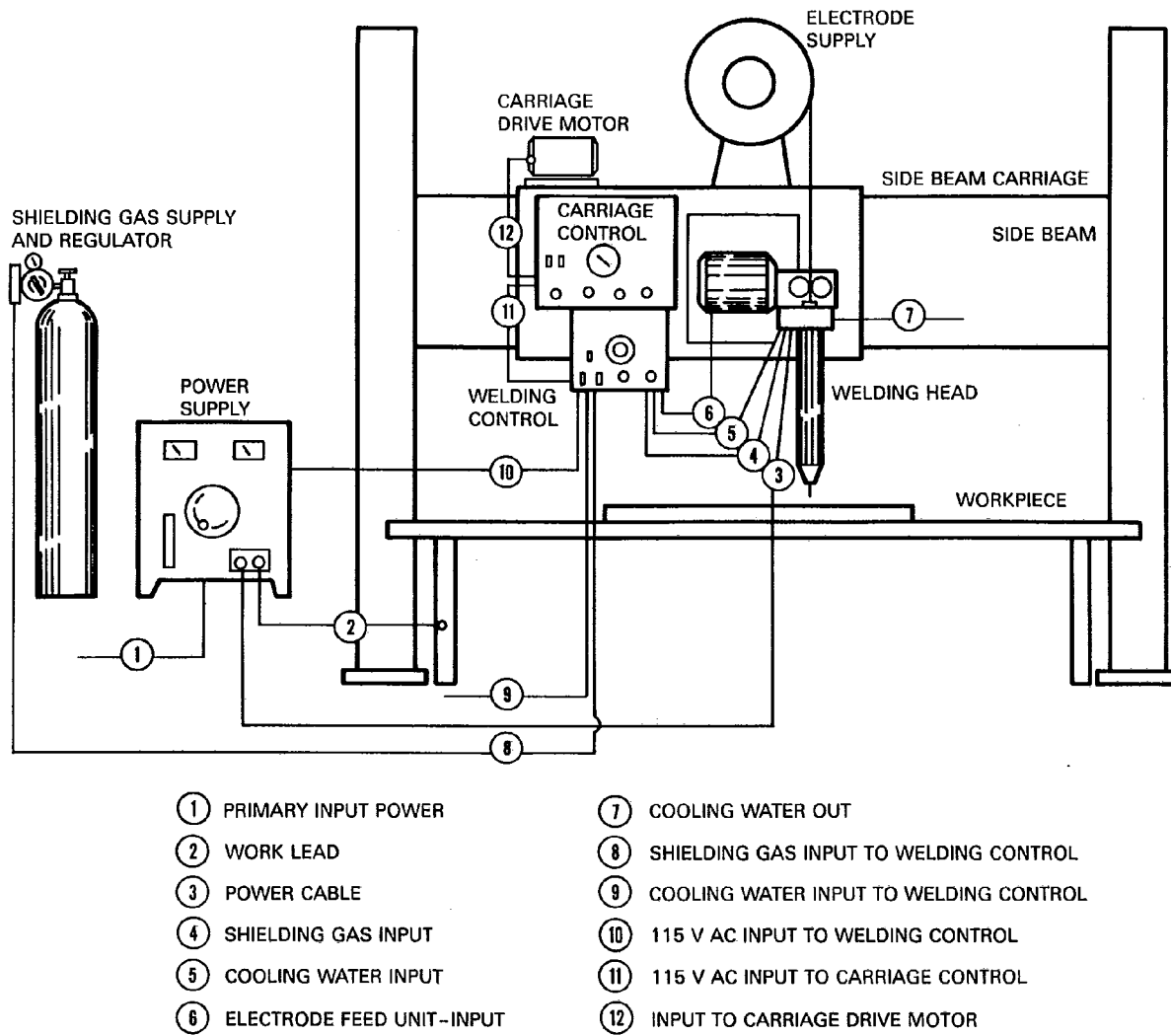


Figure 10 – Machine Gas Metal Arc Welding Installation

- (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.

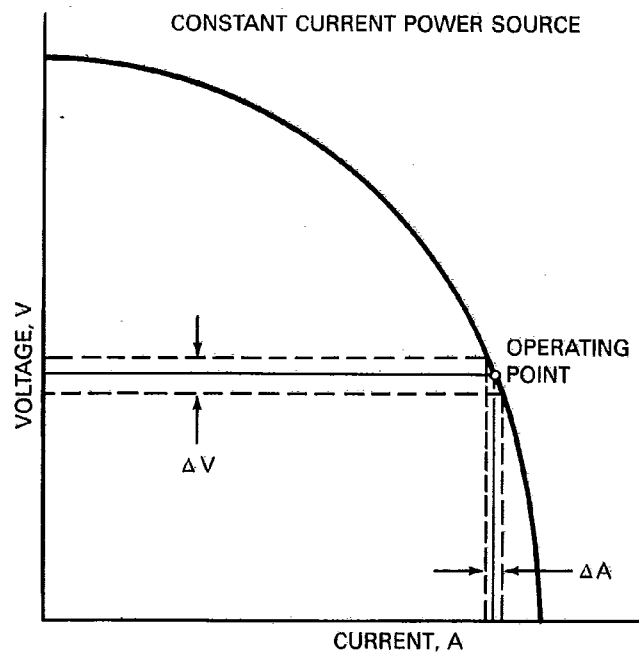
3.2.6.2 Slope. The lower illustration of Figure 11 shows the static volt-ampere slope for a GMAW constant voltage power source. The slant of the curve is referred to as the "slope" of the power source. Slope has the dimensions of resistance since: $\text{Slope} = \text{change in voltage} / \text{change in current} = (\text{volts/ampere}) = \text{ohms}$. 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.

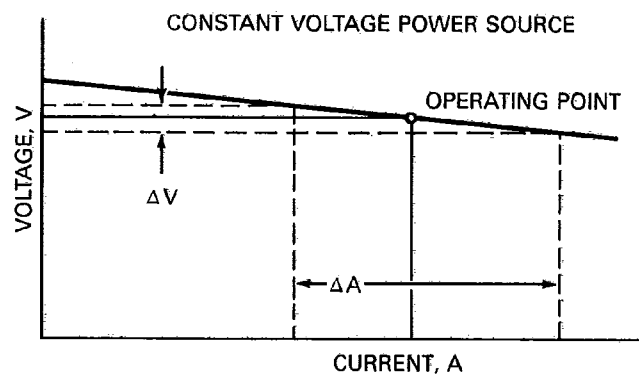
As an example, if the open circuit voltage is 48 volts and the welding condition is 28 volts and 200 amperes, the slope is calculated by determining V and A, as illustrated by Figure 13. In this case, V is 10 volts and A is 100 amperes; the slope is 10 volts per 100 amperes.

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

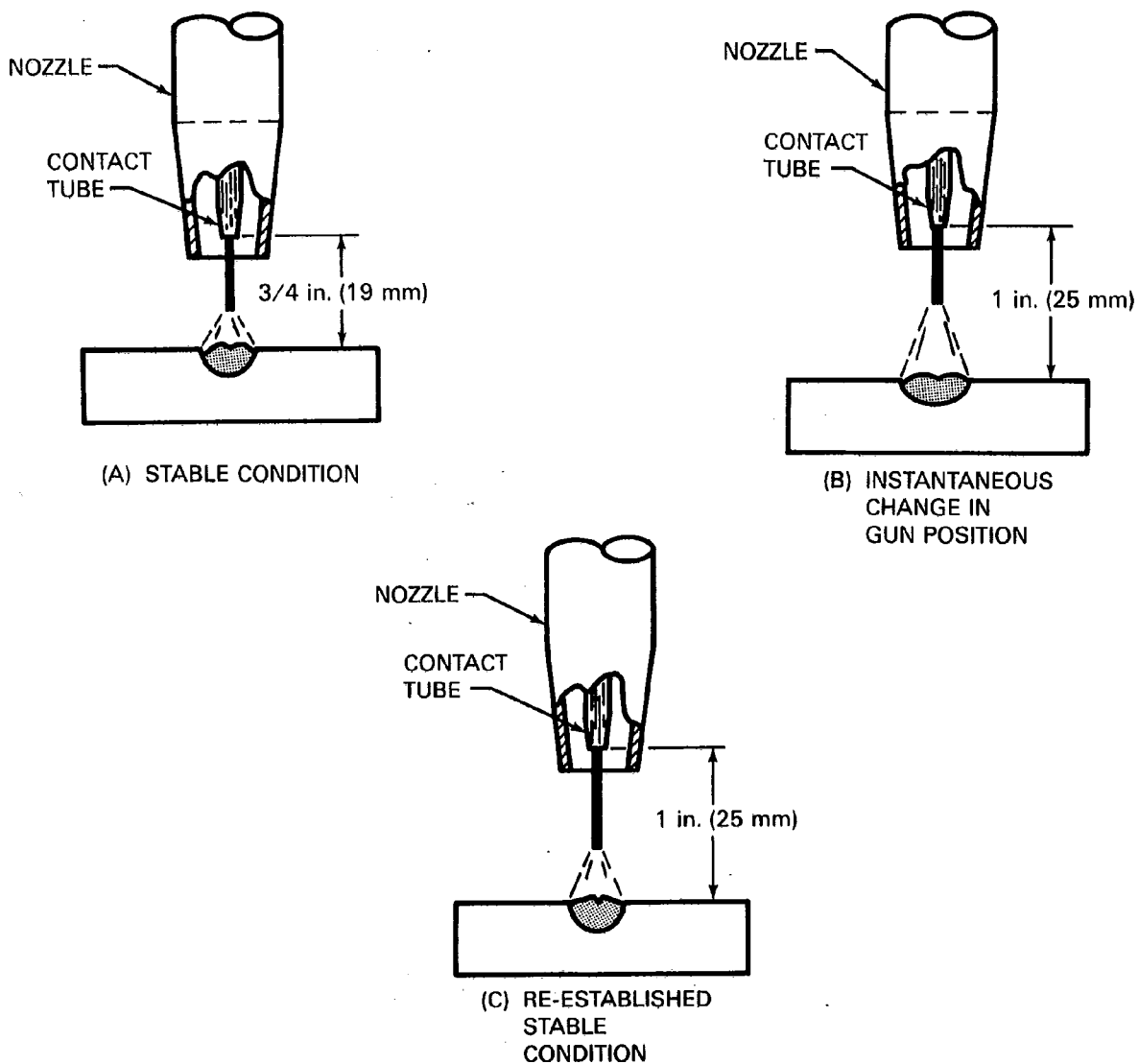


(A)



(B)

Figure 11 – Static Volt-Ampere Characteristics



ARC LENGTH	1/4 in. (6.4 mm)	1/2 in. (12.7 mm)	> 1/4 in. (6.4 mm)
ARC VOLTAGE	24 VOLTS	29 VOLTS	> 24 VOLTS
ARC CURRENT	250 AMPS	220 AMPS	< 250 AMPS
ELECTRODE WIRE FEED	250 IPM (106 mm/s)	250 IPM (106 mm/s)	250 IPM (106 mm/s)
INSTANTANEOUS MELTING RATE:	250 IPM (106 mm/s)	220 IPM (93 mm/s)	250 IPM (106 mm/s)

Figure 12 – Automatic Regulation of Arc Length in the GMAW Process with a Conventional Power Supply

force) is a function of the slope of the volt-ampere characteristics of the power source, as shown in Figure 15. Although the welding voltage and amperage of these two power sources are identical, the short circuit current of curve A is less than that of curve B. Curve A has the steeper slope or a greater voltage drop per 100 amperes as compared to curve B; i.e., the steeper the slope, the lower the short circuit current and pinch effect; the flatter the slope, the higher the short circuit current and pinch effect.

In short circuiting welding, the amount of short circuit current is important since its resultant pinch effect determines the way a molten drop detaches from the electrode. This in turn affects the arc stability. When little or no slope is present in the power source circuit, the short circuit current will rise to a very high level. At high currents, the pinch effect is also very high, and a violent parting of the molten drop takes place, acting as a fuse. The excessive pinch effect will violently squeeze the metal aside and break the short circuit, producing spatter.

When the short circuit current available from the power source is limited to low values by a steep slope, the electrode can carry the full current and the short circuit will not be broken. Under these conditions the electrode will either pile up on the workpiece or freeze to the weld pool. When the short circuit current is at the correct value, the parting of the molten drop from the electrode is smooth with very little spatter. Typical short circuit currents

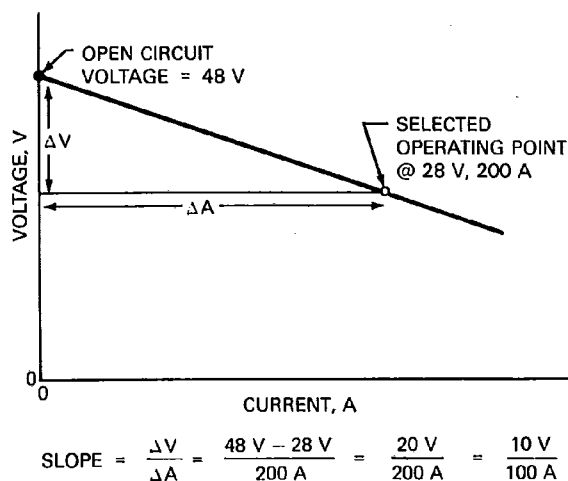


Figure 13 – Calculation of the Slope for a Power Source

required for metal transfer with the best arc stability are shown in Table 1.

Many CV power sources are equipped for changing the slope of the volt-ampere curve. They may be stepped or continuously adjustable to provide the correct short circuit current for the application involved. Some have a fixed slope which has been predetermined for a given condition of welding.

3.2.6.3 Inductance. When the load changes on a power source, the current takes a definite time to attain its new level. The circuit characteristic primarily responsible for this time lag is the inductance. This power source variable is usually measured in henrys. The effect of inductance is illustrated by the curves plotted in Figure 16. Curve A shows a typical current-time curve. As the current rises from zero to a final value, some inductance is added. This curve is said to have an exponential rate of current rise (commonly called "time rate of response"). Curve B shows the path the current would have taken if there were no inductance in the circuit.

The maximum amount of pinch effect is determined by the short circuit current level. As noted earlier, this current level is determined by the slope of the power source. The rate of increase of the pinch effect is controlled by the rate of increase of current rise. The rate of current rise is determined by the inductance of the power source. If

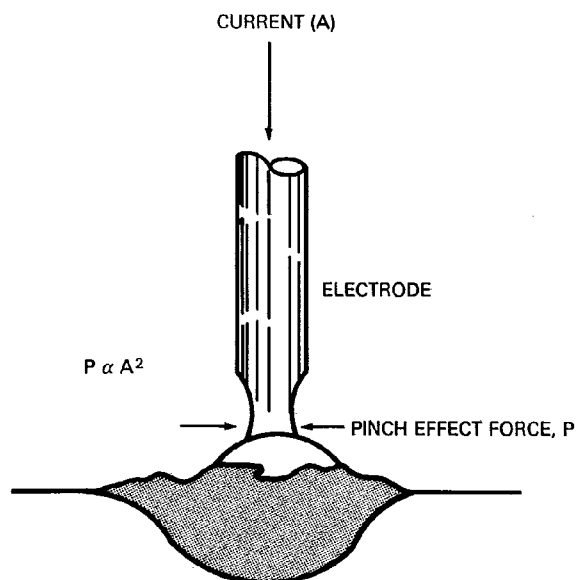


Figure 14 – Illustration of Pinch Effect During Short Circuiting Transfer

16

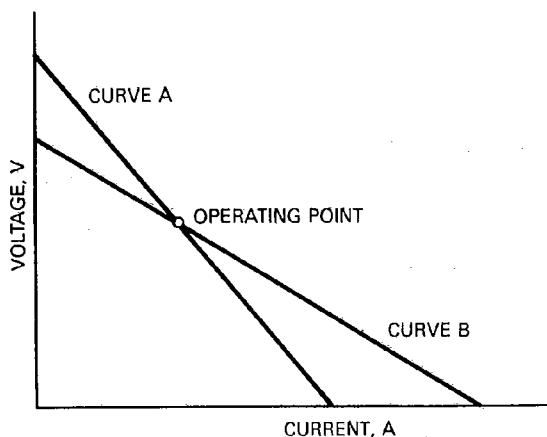


Figure 15 – Effect of Changing Slope

the pinch effect is applied rapidly, the molten drop will be violently squeezed off the electrode and cause spatter. Greater inductance will decrease the number of short circuit metal transfers per second and increase the arc-on time. This increased arc-on time results in a flatter, smoother weld bead. The opposite is true when the inductance is decreased.

In spray transfer welding, the addition of some inductance to the power source will produce a softer, more usable start without reducing the final amount of current available. Too much inductance will result in electrode stubbing on the start.

Spatter is held to a minimum when adequate current and correct rate of current rise exist. The power source adjustments required for minimum spatter conditions vary with the electrode material and size. As a general rule, both the amount of short circuit current and the amount of inductance needed for the ideal pinch effect are increased as the electrode diameter is increased.

Power sources are available with fixed, stepped, or continuously adjustable inductance levels.

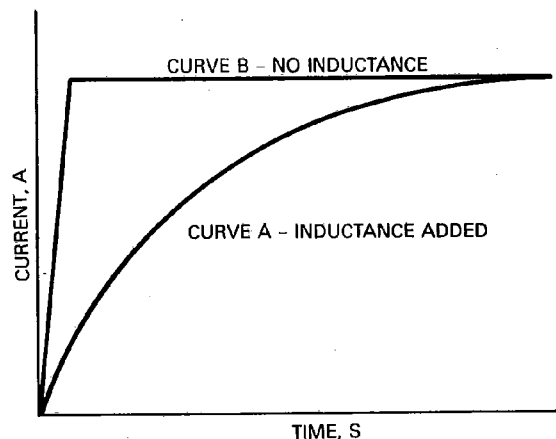


Figure 16 – Change in Rate of Current Rise Due to Added Inductance

3.3 Automatic Welding Equipment. This type of welding equipment installation is effectively used when the work can be more easily brought to the welding station or when a great deal of welding must be done. Weld travel speed and weld quality can be greatly increased because arc travel is automatic and precisely controlled.

Basically, all of the equipment is identical to that needed in a semiautomatic station except for the following changes (see Figure 10):

- (1) The welding gun is mounted directly under the electrode feed motor. The electrode conduit, gun handle, and gun switch are not used.
- (2) The welding control is mounted separately from the electrode feed motor. The welding control may have additional controls, such as preweld and postweld gas and water flow, starting speed, crater fill, and burnback.

Also, equipment such as the following is needed to provide automatic arc or workpiece travel:

- (1) Side beam carriage with motor control
- (2) Positioner or manipulator
- (3) Robotic systems

Table 1
Typical Currents (Short Circuit) for
Metal Transfer in the Short Circuiting Mode
(Power Source – Static Characteristics)

Electrode Material	Electrode Diameter		Short Circuit Current, amperes (dcep)
	in.	mm	
Carbon steel	0.030	0.8	300
Carbon steel	0.035	0.9	320
Aluminum	0.030	0.8	175
Aluminum	0.035	0.9	195

The side beam carriage is mounted on a side beam which must be parallel to the weld joint. The electrode feed motor, electrode spool, welding control, and travel speed governor are usually mounted on the side beam carriage. The carriage motor supplies movement of the carriage. The speed of travel is adjusted through connections to the governor.

Other types of equipment can be used for automatic travel. These include beams, carriages mounted on tracks, and specially built positioners and fixtures. The welding control regulates travel to coincide with the weld start and stop. Automatic welding can also be accomplished by movement of the work under a fixed welding head; for example, by attaching to, and moving the work in a weld positioner.

Robotic systems are being used more frequently today in high volume production applications. A robotic work cell is a basic subdivision of a flexible manufacturing system and consists of a robot manipulator, a controller, a part positioner, a part fixture and a welding process equipment assembly. The robot system is programmed to weld automatically along the paths of a joint which may have compound curvatures associated with it (i.e., it must operate in three dimensional space.) Recent developments with various sensors have indicated that adaptive controls to compensate for normal part or processing variations will be commonplace in the future.

4. Process Requirements and Applications

In GMAW, by definition, coalescence of metals is produced by heating them with an arc established between a continuous filler metal electrode and the work. The shielding gas and the consumable electrode are two essential requirements for this process.

4.1 Shielding Gas

4.1.1 General. Most metals exhibit a strong tendency to combine with oxygen (to form oxides) and to a lesser extent with nitrogen (to form metal nitrides). Oxygen will also react with carbon to form carbon monoxide and carbon dioxide gas. These reaction products are all a source of weld deficiencies in the form of: fusion defects due to oxides; loss of strength due to porosity, oxides, and nitrides; and weld metal embrittlement due to dissolved oxides and nitrides. Since the atmosphere is composed of approximately eighty percent nitrogen and twenty

percent oxygen, these reaction products are easily formed. The primary function of the shielding gas is to exclude the surrounding atmosphere from contact with the molten weld metal.

The shielding gas will also have a pronounced effect upon the following aspects of welding and the resultant weld:

- (1) Arc characteristics
- (2) Mode of metal transfer
- (3) Depth of fusion and weld bead profile
- (4) Speed of welding
- (5) Undercutting tendency
- (6) Cleaning action

4.1.2 The Inert Shielding Gases-Argon and Helium. Argon and helium are inert gases. These gases and mixtures of the two are necessarily used in the welding of nonferrous metals and also widely used to weld stainless steel and low alloy steels. The following are basic differences between argon and helium:

- (1) Density
- (2) Thermal conductivity
- (3) Arc characteristics

The density of argon is approximately 1.4 times that of air (heavier) while the density of helium is approximately 0.14 times that of air (lighter). The heavier the gas, the more effective it is at any given flow rate for shielding the arc and blanketing the weld area in flat position (downhand) welding. Therefore, helium shielding requires approximately two or three times higher flow rates than argon shielding, in order to provide the same effective protection.

Helium possesses a higher thermal conductivity than argon and also produces an arc plasma in which the arc energy is more uniformly dispersed. The argon arc plasma is characterized by a very high energy inner core and an outer mantle of lesser heat energy. This difference strongly affects the weld bead cross section. The helium arc produces a deep, broad, parabolic weld bead. The argon arc produces a bead cross section most often characterized by a papillary (nipple) type penetration pattern (see Figure 17).

At any given wire feed speed, the voltage of the argon arc will be noticeably less than that of the helium arc. As a result, there will be less change in the voltage with respect to change in arc length for the argon arc, and the arc will tend to be more stable than the helium arc. The argon arc (including mixtures with as low as ninety percent argon) will produce an axial spray transfer at current levels above

the transition current. The helium-shielded arc produces a metal transfer of large droplets in the normal operating range. Therefore, the helium arc will produce a higher spatter level and poorer weld face appearance compared to the argon arc.

The more readily ionized argon gas also facilitates arc starting and will provide superior surface cleaning action when used with electrode positive.

4.1.3 Mixtures of Argon and Helium. Pure argon shielding is used in many applications for welding nonferrous metals. The use of pure helium is generally restricted to more specialized areas because of its limited arc stability. However, the desirable weld bead cross section (deep, broad, and parabolic) obtained with the helium arc are quite often the objective in using an argon-helium shielding gas mixture. The result is an improved weld bead cross section plus the desirable axial spray metal transfer characteristics of argon (see Figure 17).

In short circuiting transfer, argon helium mixtures of from sixty to ninety percent helium are used to obtain higher heat input into the base metal for better fusion characteristics. For some metals, such as stainless and low alloy steels, helium additions are chosen to obtain higher heat input, instead of CO₂ additions, because helium will not produce weld metal reactions that could adversely affect the mechanical properties of the deposit.

4.1.4 Oxygen and CO₂ Additions to Argon and Helium. Pure argon and, to some extent, helium produce excellent results in welding nonferrous metals.

However, these shielding gases in the pure form do not produce the most satisfactory operational characteristics in welding ferrous metals. The arc tends to be erratic, accompanied by spatter with helium shielding, and shows a marked tendency to produce undercutting with pure argon shielding. Additions to argon of from one to five percent oxygen or from three to ten percent CO₂ (and up to twenty five percent CO₂) produce a very noticeable improvement.

The optimum amount of oxygen or CO₂ to be added to the inert gas is a function of the surface condition (mill scale) of the base metal, the joint geometry, welding position or technique, and the base metal composition. Generally, three percent oxygen or nine percent CO₂ is considered a good compromise to cover a broad range of these variables.

Carbon dioxide additions to argon also tend to enhance the weld bead by producing a more readily defined pear-shaped cross section (see Figure 18).

4.1.5 Carbon Dioxide. Carbon dioxide (CO₂) is a reactive gas widely used in its pure form for the gas metal arc welding of carbon and low alloy steels. It is the only reactive gas suitable for use alone as a shield in the GMAW process. Higher welding speed, greater joint penetration, and lower cost are general characteristics which have encouraged extensive use of CO₂ welding gas.

With a CO₂ shield, metal transfer is either of the short circuiting or globular mode. Axial spray transfer is a characteristic of the argon shield and cannot be achieved with a CO₂ shield. The globular type

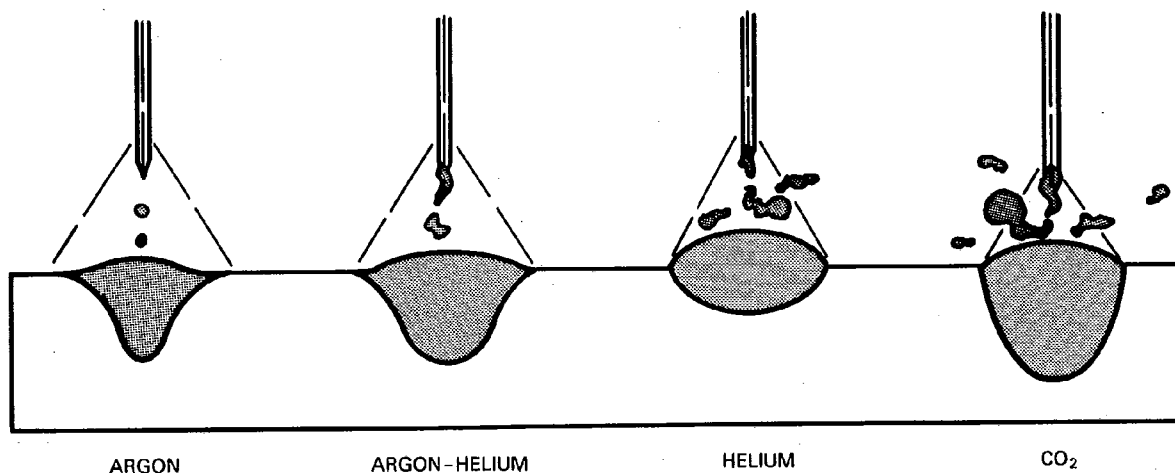


Figure 17 – Bead Cross Section and Depth of Fusion (Penetration) Patterns with Various Shielding Gases

transfer arc is harsh and produces a rather high level of spatter. This requires that the welding conditions be set with relatively low voltage to provide a very short buried arc (the tip of the electrode is actually below the surface of the work), in order to minimize spatter.

In overall comparison to the argon-rich shielded arc, the CO_2 -shielded arc produces a weld bead of excellent penetration with a rougher surface profile and much less wetting action at the extremity of the weld bead due to the buried arc. Very sound weld deposits are achieved, but mechanical properties may be adversely affected due to the oxidizing nature of the arc.

4.1.6 Shielding Gas Selection. A summary of typical usage for the various shielding gases based upon the metal being welded is shown in Tables 2, 3, and 4.

4.2 Electrodes

4.2.1 General. In the engineering of weldments, filler metals are selected to produce a weld deposit with these basic objectives:

(1) A deposit closely matching the mechanical properties and physical characteristics of the base metal

(2) A sound weld deposit, free of discontinuities

Note the first objective. A weld deposit, even one of composition identical to the base metal, will possess unique metallurgical characteristics. Therefore, the first objective of the weldment design is to produce a weld deposit composition having desired properties equal to or better than those of the base metal. The second objective is generally achieved through use of a filler metal electrode that was formulated to produce a relatively defect-free deposit.

4.2.2 Composition. The basic filler metal composition is designed to be compatible with one or more of the following base metal characteristics:

- (1) Chemistry
- (2) Strength
- (3) Ductility
- (4) Toughness

Alternate or additional consideration may be given to other properties such as corrosion, heat treatment response, wear resistance, color match, etc. All of these considerations, however, are secondary to the metallurgical compatibility of the base metal to the filler metal.

American Welding Society specifications have been established for filler metals in common usage. Table 5 provides a basic guide to some typical base-metal to filler-metal combinations along with the applicable AWS filler metal specification. Other filler metal compositions for special applications, such as for high-strength steels, are available.

4.2.3 Formulation. The electrode must also meet certain demands of the process regarding arc stability, metal transfer behavior, and solidification characteristics. Deoxidizers or other scavenging agents are always added to compensate for base metal reactions with oxygen, nitrogen, and hydrogen from the surrounding atmosphere or the base metal. The deoxidizers most frequently used in steel are silicon and manganese. Some steel electrodes may also use aluminum for additional deoxidation, as well as titanium and zirconium for denitrating. Nickel alloy electrodes generally use titanium and zirconium for deoxidation, and copper alloys will use titanium and silicon or phosphorus for the same purpose.

4.3 Selection of Process Variables. Many process variables must be considered for complete applica-

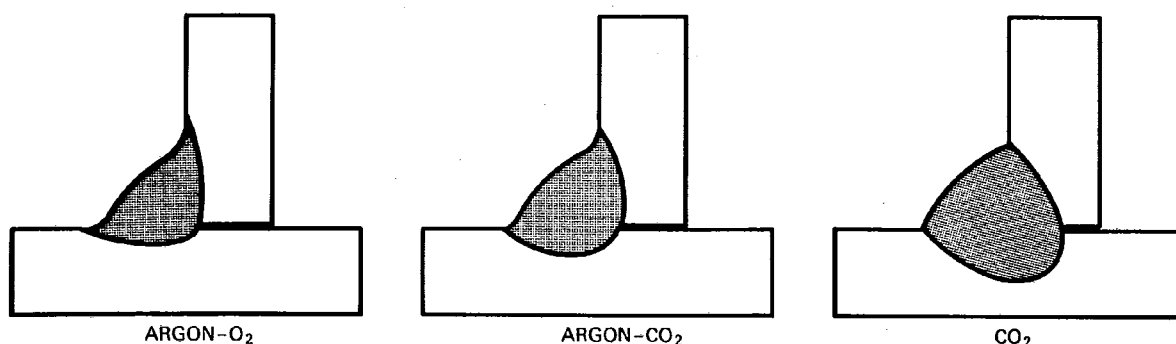


Figure 18 – Relative Effect of O_2 Versus CO_2 Additions to the Argon Shield

tion of GMAW. These variables are found in the following three principal areas:

- (1) Equipment selection
- (2) Mode of metal transfer and shielding gas
- (3) Electrode selection

These three areas are very much interrelated.

4.3.1 Equipment Selection. A variety of options and basic equipment designs is available for equipment selection. Equipment should be selected that will fit the product application and the weldment design, since the equipment must possess the capacity to do the job. Range of power output, range of open circuit voltage, static and dynamic characteristics, wire feed speed range, etc., must correspond to the weldment design (in particular, weld size) and the electrode size selected. Also to be considered are the accessories required for the selected mode of metal transfer and any other special requirements.

When new equipment is to be purchased, some consideration should be given to the versatility of the equipment and to standardization. Selection of equipment for single-purpose or high volume production can generally be based upon the requirements of that particular application only. However, if a multitude of jobs is to be performed (as in a job shop operation), many of which may be unknown at

the time of selection, versatility is very important. Other equipment already in use at the facility should be considered. Standardizing certain components and complementing existing equipment will minimize inventory requirements and provide maximum efficiency of overall operation.

4.3.2 Mode of Metal Transfer and Shielding Gas. The characteristics of the mode of metal transfer are very important in analysis of the process application. Characteristics such as weld bead cross section, reinforcement shape, spatter, etc., are relevant to the weldment design. The following major considerations reflect the importance of these characteristics.

4.3.2.1 Design and Service Performance. Product design, as well as specific weld joint design, requires consideration of root penetration and reinforcement cross sections. Both static and dynamic service performance requirements may dictate the need for additional strength (in the form of penetration) or minimal stress concentration (good wetting characteristics). The shielding gas selection is very important in determining these basic characteristics.

4.3.2.2 Process Control. Metal thickness may require using the pulse current or low energy short

Table 2
Shielding Gases and Gas Mixtures for GMAW

Shielding Gas	Chemical Behavior	Typical Application
Argon	Inert	Virtually all metals except steels.
Helium	Inert	Aluminum, magnesium, and copper alloys for greater heat input and to minimize porosity.
Ar + 20-80% He	Inert	Aluminum, magnesium, and copper alloys for greater heat input and to minimize porosity (better arc action than 100% helium).
Nitrogen		Greater heat input on copper (Europe).
A + 25-30% N ₂		Greater heat input on copper (Europe); better arc action than 100 percent nitrogen.
Ar + 1-2% O ₂	Slightly oxidizing	Stainless and alloy steels; some deoxidized copper alloys.
Ar + 3-5% O ₂	Oxidizing	Carbon and some low-alloy steels.
CO ₂	Oxidizing	Carbon and some low-alloy steels.
Ar + 20-50% CO ₂	Oxidizing	Various steels, chiefly short circuiting mode.
Ar + 10% CO ₂ + 5% O ₂	Oxidizing	Various steels (Europe).
CO ₂ + 20% O ₂	Oxidizing	Various steels (Japan).
90% He + 7.5% Ar + 2.5% CO ₂	Slightly oxidizing	Stainless steels for good corrosion resistance, short circuiting mode.
60 to 70% He + 25 to 35% Ar + 4 to 5% CO ₂	Oxidizing	Low-alloy steels for toughness, short circuiting mode.

Table 3
Selection of Gases for GMAW with Spray Transfer

Metal	Shielding Gas	Advantages
Aluminum	Argon	0 to 1 in. (0 to 25 mm) thick; best metal transfer and arc stability; least spatter.
	35% argon +65% helium	1 to 3 in. (25 to 76 mm) thick; higher heat input than straight argon; improved fusion characteristics with 5XXX series Al-Mg alloys.
	25% argon	Over 3 in. (76 mm) thick; highest heat input; minimizes porosity.
Magnesium	Argon	Excellent cleaning action.
Carbon steel	Argon	Improves arc stability; produces a more fluid and controllable weld puddle; good coalescence and bead contour; minimizes undercutting; permits higher speeds than pure argon.
	+3-5% oxygen	Less oxidation of weld than Argon-O ₂ mixtures; better penetration pattern and bead wetting comparable to Argon +3-5% O ₂ .
Low-alloy steel	Argon +5-10% Carbon dioxide	Minimizes undercutting; provides good toughness.
	Argon + 2% oxygen	Less oxidation of weld than Argon-O ₂ mixtures; better penetration pattern and bead wetting comparable to Argon +3-5% O ₂ .
	Argon +2-8% Carbon dioxide	Improves arc stability; produces a more fluid and controllable weld puddle, good coalescence and bead contour; minimizes undercutting on heavier stainless steels.
Stainless steel	Argon +1% oxygen	Provides better arc stability, coalescence, and welding speed than 1 percent oxygen mixture for thinner stainless steel materials.
	Argon +2% oxygen	Provides good wetting; decreases fluidity of weld metal for thickness up to and their alloys 1/8 in. (3.2 mm).
Copper, nickel, and their alloys	Argon	Higher inputs of 50 & 75 percent mixtures offset high heat dissipation of heavier gages.
	+helium	Good arc stability; minimum weld contamination; inert gas backing is required to prevent air contamination on back of weld area.
Titanium	Argon	

circuit transfer mode rather than either the spray or globular transfer mode with their inherently higher energy input. Joint tolerances (gap) and weld size and length may also be a major influence in selection of the process mode to be used.

The desired weld bead cross section (including reinforcement, fusion pattern, and penetration) can be controlled by the shielding gas selection. Proper shielding gas selection can be an important factor to assure, for instance, good fusion characteristics when welders may be extended to maintain their gun in an optimum position.

4.3.2.3 Appearance. The appearance of the weldment is not of technical concern, but may be important. Smooth and spatter free weld beads on a product in an area highlighted in the purchaser's view are cited as a sales factor in many instances. The spray arc and the short circuiting modes of metal transfer will produce the smoothest and neatest-appearing welds. Smooth and spatter-free areas adjacent to GMAW welds may also be required to assure proper fits in subsequent final assembly operations.

4.3.3 Electrode Selection. The selection of the welding electrode should be based principally upon matching the mechanical properties and the physical characteristics of the base metal (see 4.2 and Table 5). Secondary consideration should be given to items such as the equipment to be used, the weld size (deposition rates to be utilized), existing electrode inventory, and materials handling systems.

4.3.3.1 Equipment. The electrode package size should be compatible with the available handling equipment. The package size should be determined by a cost evaluation that considers product volume, change time versus the consideration of available space, inventory cost, and the materials handling system.

4.3.3.2 Weld Size. The electrode diameter should be chosen to best fit the requirements of the weld size and the deposition rate to be used.

4.3.3.3 Standardization and Inventory. Evaluation of each welding job on its own individual merit would require an increasingly larger inventory with

Table 4
Selection of Gases for GMAW with Short Circuiting Transfer

Metal	Shielding Gas	Advantages
Carbon	75% argon +25% CO ₂	Less than 1/8 in. (3.2 mm) thick; high welding speeds without burn-thru; minimum distortion and spatter.
	75% argon +25% CO ₂	More than 1/8 in. (3.2 mm) thick; minimum spatter; clean weld appearance; good puddle control in vertical and overhead positions.
	CO ₂	Deeper penetration; faster welding speeds.
Stainless steel	90% helium +7.5% argon+2.5% CO ₂	No effect on corrosion resistance; small heat affected zone; no undercutting; minimum distortion.
Low-alloy steel	60-70% helium +25-35% argon +4-5% CO ₂	Minimum reactivity; excellent toughness; excellent arc stability; wetting characteristics, and bead contour; little spatter.
	75% argon +25% CO ₂	Fair toughness; excellent arc stability, wetting characteristics, and bead contour; little spatter.
Aluminum, copper magnesium, nickel and their alloys	Argon & argon + helium	Argon satisfactory on sheet metal; argon-helium preferred on thicker sheet material (over 1/8 in. [3.2 mm]).

an increasing number of jobs. Minimizing inventory requires a review of overall welding requirements in the plant, with standardization of the basic electrode composition and sizes as well as the electrode packages as the objective. This can be accomplished readily with minimum compromise since quite broad and overlapping choices are available.

4.3.3.4 Materials Handling Systems. The electrode package size should also take into account the requirements for handling. Generally speaking, one individual can be expected to change an electrode package weighing up to 60 lb (27 kg) without assistance. However, some systems are designed so that an individual can handle the larger spools up to 1000 lb (454 kg) without additional assistance. The larger packages necessitate a handling system (lift truck or similar) capable of moving the electrode package from storage to the welding station when required for changing, or additional space is needed to accommodate at least two packages in order to avoid delays.

4.4 Welding Variables. Table 6 shows the relationship between current and wire feed speed, travel speed, voltage and wire diameter. Some of the process variables to be considered are the following:

- (1) Deposition rate-travel speed
- (2) Wire feed speed (welding current)
- (3) Welding Voltage
- (4) Electrode extension
- (5) Travel Speed
- (6) Electrode Diameter

(7) Shielding gas

(8) Gun angle

4.4.1 Deposition Rate. The deposition rate is defined as the actual amount of usable metal deposited per unit of time [generally in terms of pounds (kilograms) per hour]. Deposition rate is proportional to wire feed speed. See Figures 20, 22, 25, 27, 29, and 32. It is necessary to balance the deposition rate against the travel speed, since proper balance achieves an optimum rate of metal deposition for the weld joint design. This is particularly important in semiautomatic welding where weld quality depends upon the physical movement capability of the welder to retain control of the weld puddle as travel speed is increased. The maximum travel speed limitation is about 25 ipm maximum (11 mm/s), although in some reported instances, the travel speed may reach as high as 150 ipm (64 mm/s). In general, these higher rates of travel speed are attainable when the weld size is very small, the weld length is very short, the weld is along a straight line, or when optimum weld quality is not a factor.

4.4.2 Welding Current-Wire Feed Speed. After determining the optimum deposition rate for the application, the next step is to determine the welding current and the related wire feed speed to achieve that deposition rate. In a practical application, the deposition rate is more accurately set, maintained, and reproduced by measurement of the wire feed speed rather than the welding current value.

4.4.3 Welding Voltage. The welding voltage (related to the proper arc length) is established to maintain arc stability at the chosen electrode feed speed or welding current level and to minimize spatter.

4.4.4 Electrode Extension. The basic control settings for low conductivity electrode metals are very much dependent upon the electrode extension. Variation in electrode extension results in a change in the electrical characteristics of the balanced system, as determined by the resistivity of the electrode length between the contact tube and the arc (see Figure 19).

In essence, as the contact tube-to-work distance is increased, the I^2R heating effect is increased, thus decreasing the welding current (I) required to melt the electrode. Conversely, as the contact tube-to-work distance is decreased, the I^2R effect

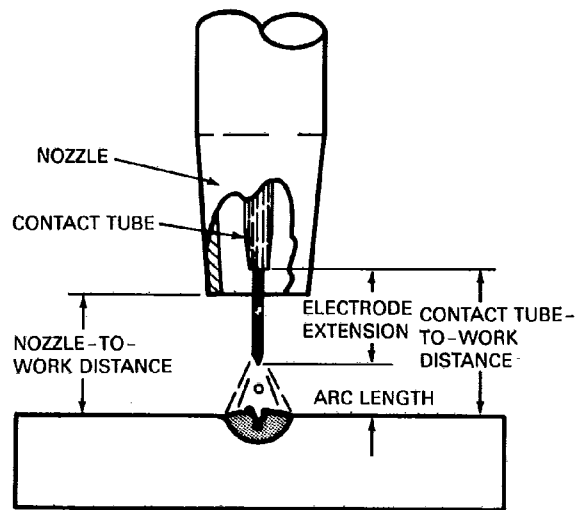


Figure 19 – Electrode Extension

Table 5
Recommended Filler Metals for GMAW

Base Metal Type	Recommended Electrode		AWS Filler Metal Specification (Use Latest Edition)	Current Range		
	Material Type	Electrode Classification		Electrode Diameter		Amperes
Aluminum and aluminum alloys	1100	ER1100 or ER4043	A5.10	0.030	0.8	50-175
	3003,3004	ER1100 or ER5356		3/64	1.2	90-250
	5052,5454	ER5554,ER5356 or ER5183		1/16	1.6	160-350
	5083,5086,5456	ER5556 or ER5356		3/32	2.4	225-400
	6061,6063	ER4043 or ER5356		1/8	3.2	350-475
Magnesium alloys	AZ10A	ERAZ61A,ERAZ92A	A5.19	0.040	1.0	150-300*
	AZ31B,AZ61A			3/64	1.2	160-320*
	AZ80A	ERAZ61A,ERAZ92A		1/16	1.6	210-400*
	ZE10A	ERAZ61A,ERAZ92A		3/32	2.4	320-510*
	ZK21A	ERAZ61A,ERAZ92A		1/8	3.2	400-600*
	AZ63A,AZ81A					
	AZ91C	ERAZ92A				
	AZ92A,AM100A	ERAZ92A				
	HK31A,HM21A, HM31A	EREZ33A				
	LA141A	EREZ33A				
Copper and copper alloys	Deoxidized copper	ECu	A5.6	0.035	0.9	150-300
	Cu-Ni alloys	ECuNi		0.045	1.2	200-400
	Manganese bronze	ECuA1-A2		1/16	1.6	250-450
	Aluminum bronze	ECuA1-B		3/32	2.4	350-550
	TW bronze	ECuSn-A				

*Spray Transfer Mode

(continued)

Table 5 (Continued)
Recommended Filler Metals for GMAW

Base Metal Type	Recommended Electrode		AWS Filler Metal Specification (Use Latest Edition)	Current Range						
				Electrode Diameter		Amperes				
	Material Type	Electrode Classification		in.	mm					
Nickel and nickel alloys	Monel**Alloy 400 Inconel**Alloy 600	ERNiCu-7 ERNiCrFe-5	A5.14	0.020	0.5	---				
				0.030	0.8	---				
				0.035	0.9	100-160				
				0.045	1.2	150-260				
				1/16	1.6	100-400				
Titanium and titanium alloys	Commercially pure Ti-0.15 Pd Ti-5Al-2.5Sn	Use a filler metal one or two grades lower ERTi-0.2Pd ERTi-5Al-2.5Sn or comm. pure	A5.16	0.030	0.8	---				
				0.035	0.9	---				
				0.045	1.2	---				
				Austenitic stainless steels	Type 201 Types 301,302, 304 & 308 Type 304L Type 310 Type 316 Type 321 Type 347	ER308 ER308 ER308L ER310 ER316 ER321 ER347	A5.9	0.020	0.5	---
								0.025	0.6	---
0.030	0.8	75-150								
0.035	0.9	100-160								
0.045	1.2	140-310								
1/16	1.6	280-450								
5/64	2.0	---								
3/32	2.4	---								
Carbon steels	Hot rolled or cold-drawn plain carbon steels	ER70S-3,or ER70S-1 ER70S-2,ER70S-4 ER70S-5,ER70S-6	A5.18	7/64	2.8	---				
				1/8	3.2	---				
				0.020	0.5	---				
				0.025	0.6	---				
				0.030	0.8	40-220				
				0.035	0.9	60-280				
				0.045	1.2	125-380				
				0.052	1.3	160-450				
1/16	1.6	275-475								
5/64	2.0	---								
3/32	2.4	---								
1/8	3.2	---								

**Trademark-International Nickel Co.

is decreased, thus increasing the welding current requirements for a given wire feed speed. Long extension may result in lack of fusion when welding thick material. This is why it is important to maintain proper contact tube-to-work distance. Some typical values are 1/4 in. to 1/2 in. for short circuit transfer and 1/2 in. to 1 in. (13 to 25 mm) for other types of metal transfer associated with GMAW (globular and axial spray). Table 6 illustrates the relationship between welding variables and the weld.

4.4.5 Travel Speed. Travel speed is a very im-

portant variable in gas metal arc welding. If a welder lets the welding arc play on the weld pool instead of on the base metal, incomplete fusion or cold lap defect will result. A liquid weld pool acts as an insulator between the high temperature welding arc and the base material. Therefore, to consistently obtain fused metal, the welding arc must be continually positioned at the leading edge of the weld pool.

4.4.6 Guidelines for Operating Conditions. Figures 20 through 33 illustrate the basic concept of and provide basic information for establishing de-

position-rate to wire-feed-speed relationships. The distinction should be made between the melting rate (rate of melting of the electrode) and the deposition rate (rate of actual metal deposited). The two are not the same, due to arc and spatter loss, but are related by the arc transfer efficiency. Also note that the relationship between electrode feed speed and welding current can be altered by the electrode extension (not shown in these figures).

5. General Joint Design

Typical weld joint designs and dimensions for the GMAW process, as used in the welding of steel, are shown in Figure 34(A) through (D). The dimensions indicated are those that have generally been found necessary to obtain complete joint penetration and acceptable reinforcement and weld bead cross sections with suitable welding procedures.

The deep penetration characteristics of the high energy modes of GMAW (i.e., not including short circuit or pulsed current transfer) present a potential reduction in the quantity of required weld metal and, consequently, welding costs. However, care must be exercised in the reduction of groove weld

angles and depths, since penetration characteristics will tend to diminish due to greater absorption of arc energy by the side walls as the groove narrows. This is in comparison to a square-groove weld joint for which most of the arc energy is transmitted directly into the interface.

The penetration can be readily predicted in fillet welding (see Figure 35), where the side walls are generally at a 90° angle. Table 7 shows fillet size reduction possible with greater throat depth. Since the heat input is quite low with a short circuiting welding arc, the possibility of incomplete fusion defects is increased on heavier weldments.

6. Arc Spot Welding

Arc spot welding with GMAW requires the same equipment as previously described plus a special arc timer to control the arc on time, and a special gun nozzle. The gun nozzle provides containment with vents, for shielding gas, maintains a constant contact tube height when placed on top of the joint to be welded, and helps shield the welder's eyes from the arc.

Table 6
How Changes in Welding Variables Affect Weld

WELDING VARIABLES TO CHANGE	DESIRED CHANGES							
	PENETRATION		DEPOSITION RATE		BEAD SIZE		BEAD WIDTH	
	INCREASE	DECREASE	INCREASE	DECREASE	INCREASE	DECREASE	INCREASE	DECREASE
CURRENT AND WIRE FEED SPEED	↑	↓	↑	↓	↑	↓	○	○
VOLTAGE	□	□	○	○	○	○	↑	↓
TRAVEL SPEED	□	□	○	○	↓	↑	↓	↑
ELECTRODE EXTENSION	↓	↑	*↑	*↓	↑	↓	↓	↑
WIRE DIAMETER	↓	↑	↓	↑	○	○	○	○
SHIELD GAS %O ₂	↑	↓	○	○	○	○	↑	↓
GUN ANGLE	DRAG	PUSH	○	○	○	○	PUSH	DRAG

□ NO EFFECT

○ LITTLE EFFECT

↑ INCREASE

↓ DECREASE

* IF CURRENT LEVELS ARE MAINTAINED BY ADJUSTMENT OF
WIRE FEED SPEED

Table 7
Strength Equivalents (Effective Throat Depth) by Process for Fillet Welds

Design Size		Equivalent Fillet Size (By Process)						Effective Throat, Min	
		SMAW E70XX Electrode		GMAW, E70S-X Electrode					
				Argon-Rich Shielding		CO ₂ Shielding			
in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
1/8	3.2	1/8	3.2	1/8*	3.2	1/8*	3.2	0.086	2.08
5/32	4.0	5/32	4.0	1/8*	3.2	1/8*	3.2	0.111	2.82
3/16	4.8	3/16	4.8	5/32*	4.0	1/8*	3.35	0.135	3.35
1/4	6.4	1/4	6.4	3/16	4.8	5/32*	4.0	0.177	4.50
5/16	8.0	5/16	8.0	1/4	6.4	3/16	4.8	0.221	5.61
3/8	9.5	3/8	9.5	5/16	8.0	1/4	6.4	0.266	6.76
7/16	11.1	7/16	11.1	3/8	9.5	5/16	8.0	0.310	7.87
1/2	12.7	1/2	12.7	7/16	11.1	3/8	9.5	0.353	8.97
9/16	14.3	9/16	14.3	1/2	12.7	7/16	11.1	0.396	10.06
5/8	15.9	5/8	15.9	9/16	14.3	1/2	12.7	0.441	11.20

*Automatic welds only – size too small to produce a quality weldment with semiautomatic welding in the high energy mode.

NOTE:

1. Fillet welds made with low energy GMAW modes (i.e., short circuit and pulsed current transfer) exhibit the same "effective" throat depth as fillets made with the SMAW process.
2. In multiple-pass welding, effective penetration is a function of the first pass only. Applicable to both flat and horizontal singel pass welds.
3. Inspection of fillet weld cross section should be made to assure adequate welding procedure for minimum effective throat.

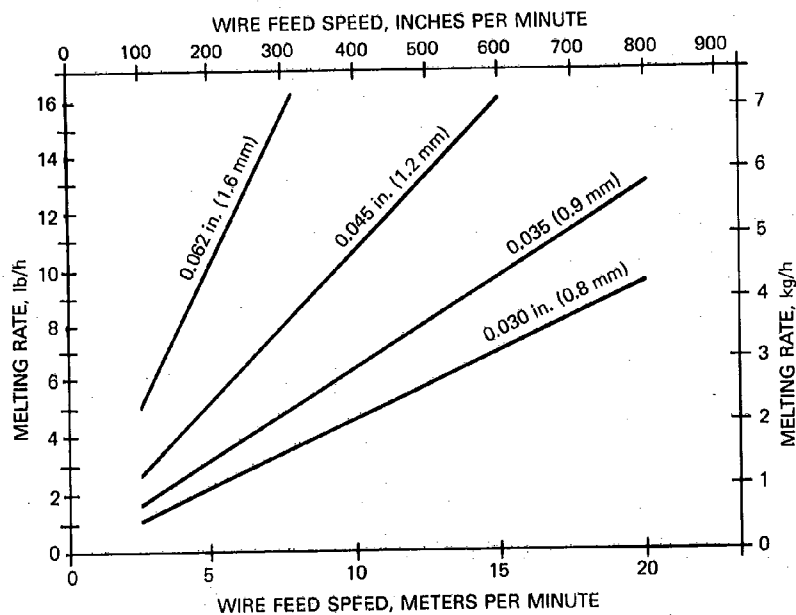


Figure 20 – Typical Melting Rates for Plain Carbon Steel

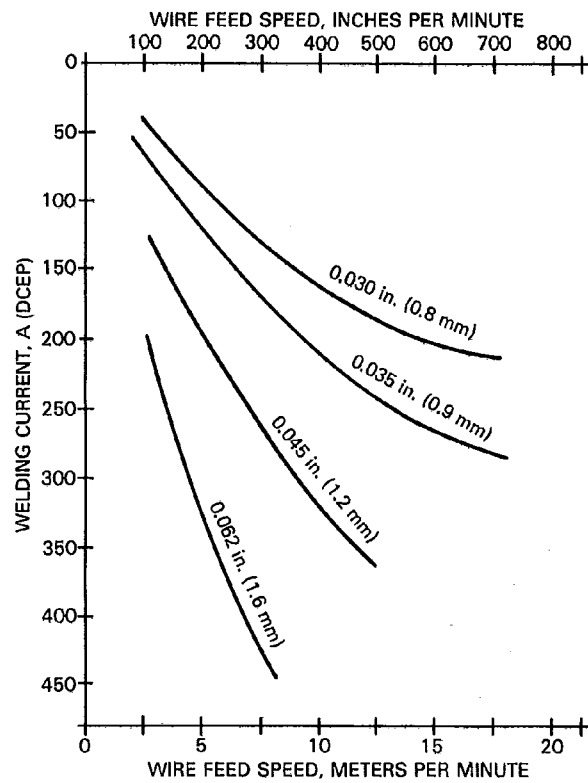


Figure 21 – Typical Welding Currents Versus Wire Feed Speeds for Carbon Steel Electrodes

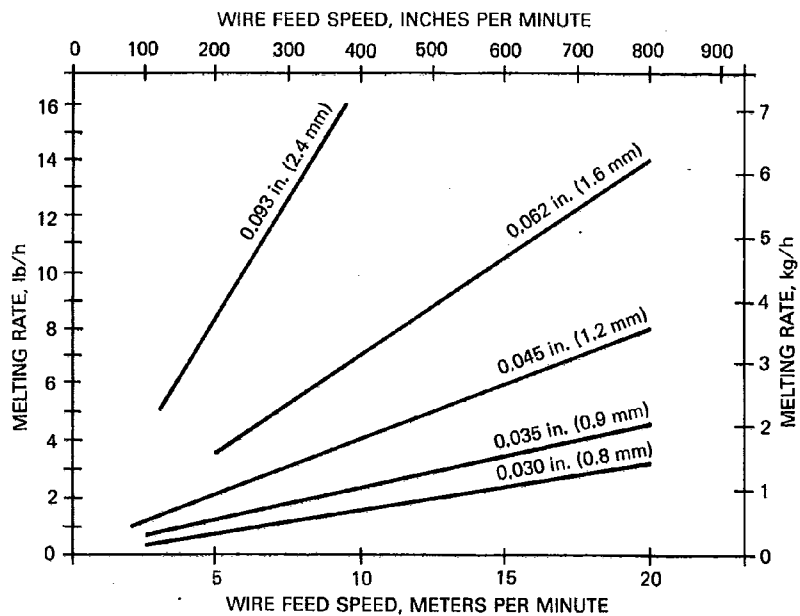


Figure 22 – Typical Melting Rates for Aluminum Electrodes

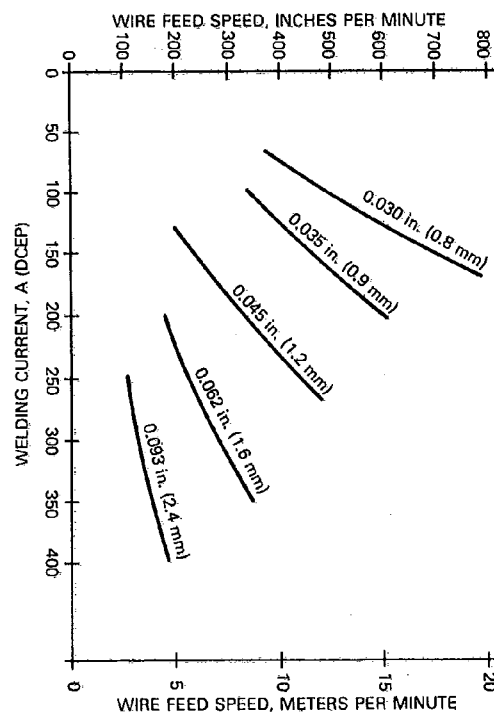


Figure 23 – Welding Currents Versus Wire Feed Speed for ER4043 Aluminum Electrodes

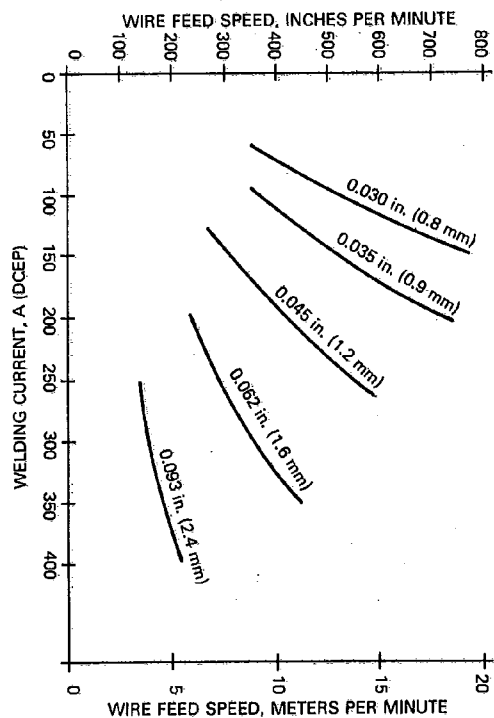


Figure 24 – Welding Currents Versus Wire Feed Speed for ER5356 Aluminum Electrodes

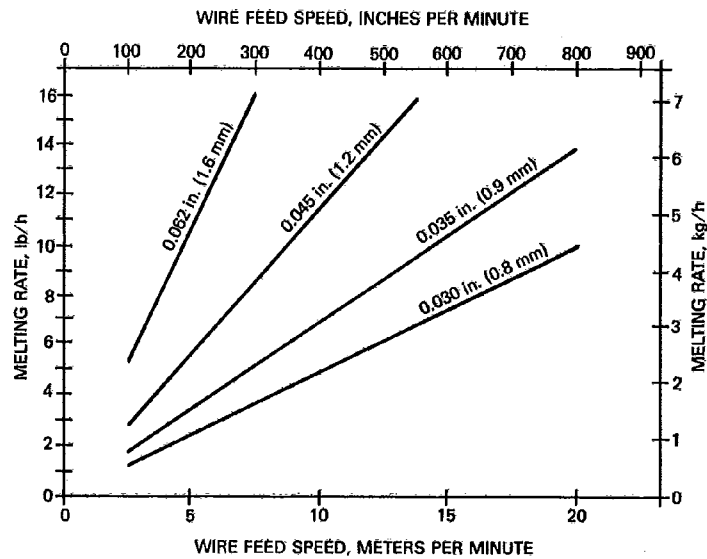


Figure 25 – Typical Melting Rates for 300 Series Stainless Steel Electrodes

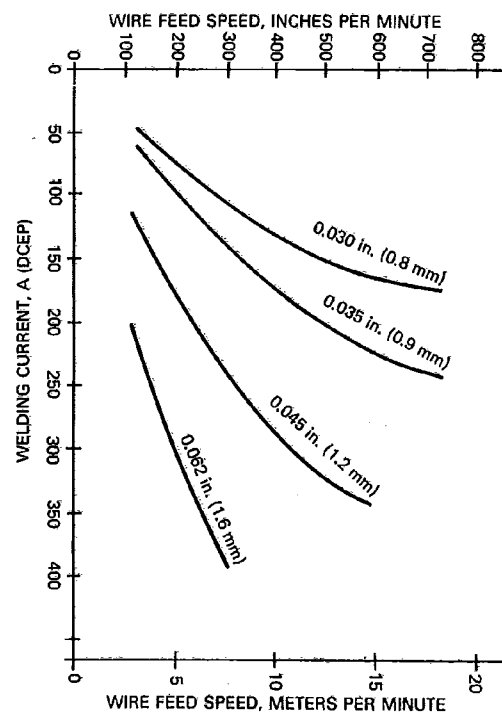


Figure 26 – Typical Welding Currents Versus Wire Feed Speeds for 300 Series Stainless Steel Electrodes

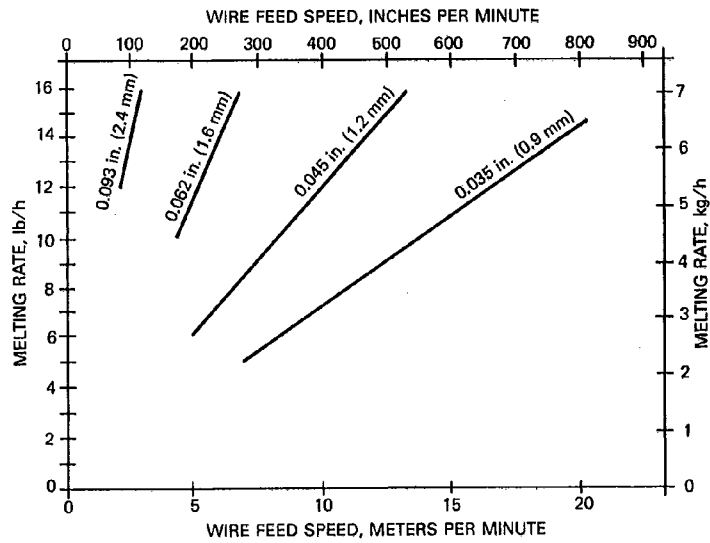


Figure 27 – Typical Melting Rates for ECu Copper Electrodes

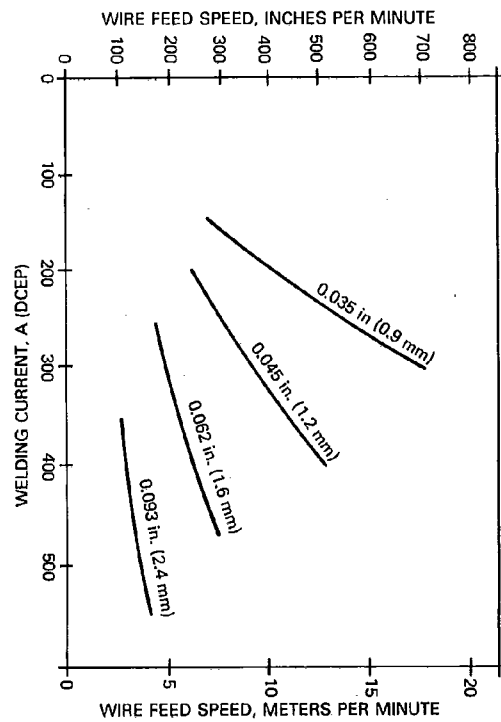


Figure 28 – Welding Currents Versus Wire Feed Speed for ECu Copper Electrodes

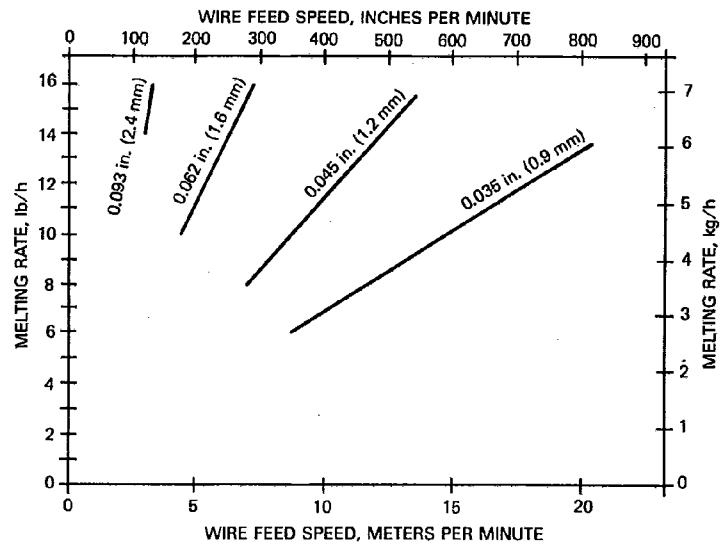


Figure 29 - Typical Melting Rates for ECuSi-A Copper Electrodes

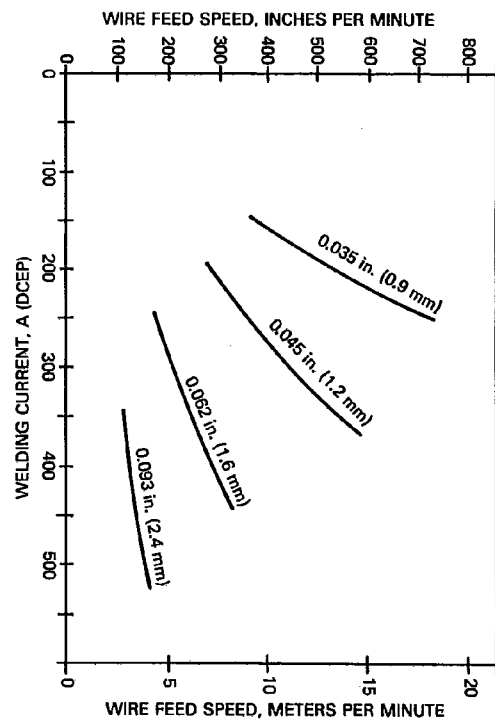


Figure 30 - Welding Currents Versus Wire Feed Speed for ECuSi-A Copper Electrodes

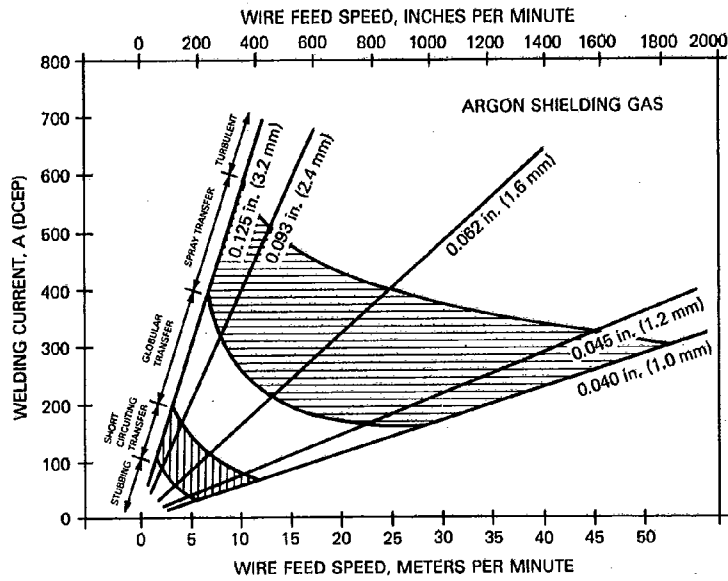


Figure 31 – Typical Currents Versus Wire Feed Speed for Magnesium Electrodes

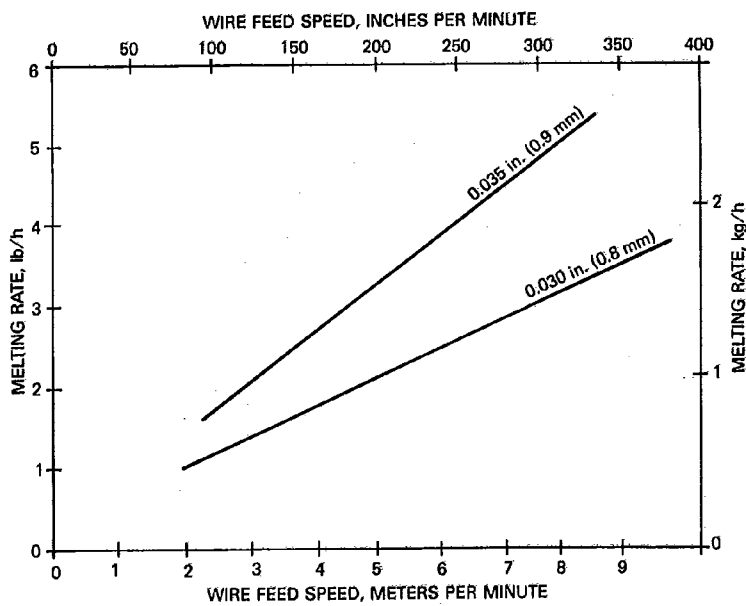


Figure 32 – Optimum Short Circuit Transfer for Plain Carbon Steel Electrodes

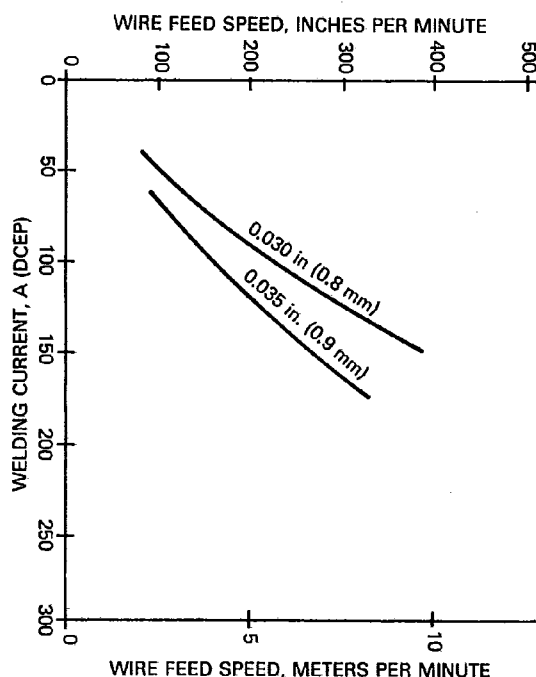


Figure 33 – Optimum Short Circuit Transfer for Carbon Steel Electrodes

6.1 Equipment Operation. The welding gun is placed in position against the workpiece and the gun's trigger is depressed to start the functions of the arc timer and the initiation of the arc. The arc is maintained by the continuously-fed consumable electrode and melts through the top sheet and fuses into the bottom sheet without relative travel. The time cycle is set to maintain the arc until the melt-through and fusing sequence is complete; i.e., the spot weld has been completed. The electrode will continue to feed during the arc cycle and will produce a slight convex reinforcement on the upper surface of the top sheet.

The controls on the arc timer and their functions are as follows:

(1) Arc time potentiometer – regulates time that welding arc is sustained

(2) Preflow time potentiometer – sets time at which gas valve opens prior to welding arc initiation (adjustable from 0 to 2 seconds)

(3) Burnback time potentiometer – controls the delay of the welding contactor drop-out after the electrode feed motor stops and the distance that the electrode melts back from the weld surface (adjustable from 0 to 0.5 seconds)

(4) Postflow time potentiometer – adjusts the time duration that shielding gas will flow after welding arc stops (adjustable from 0 to 2 seconds).

6.2 Effect of Process Variables on Weld Characteristics. Weld diameter at the interface and reinforcement are two characteristics of GMAW spot weld which determine whether the weld will satisfy the intended service. Each of the three major process variables of weld current, voltage, and weld time affect one or both of these factors. Arc voltage and welding current are relatively high for spot welding in comparison to typical GMAW values, but the time cycle for making spot welds ranges from only 0.3 seconds to 5 seconds. Guidelines for these variables are presented in Tables 8 through 12.

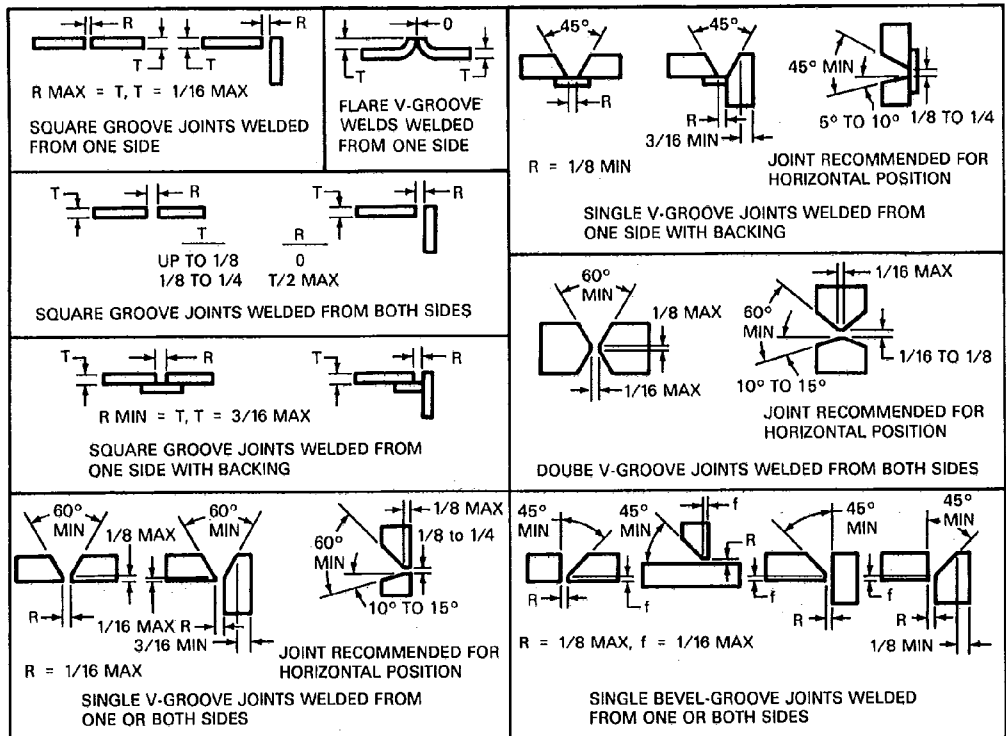
6.2.1 Current. Current has the greatest effect on penetration. Penetration is increased by using higher currents with corresponding increase in the wire feed speed. Increased penetration will generally result in a larger weld diameter at the interface.

6.2.2 Arc Voltage. The arc voltage has the greatest effect on the arc spot weld shape. In general, with current being held constant, an increase in the arc voltage will increase the diameter of the fusion zone and the diameter of the weld nugget. However, it also causes a slight decrease in the reinforcement. Arc voltages that are too high create heavy spatter conditions.

6.2.3 Weld Time. Welding conditions should be selected that produce a suitable weld within a time of 20 to 100 cycles of a 60 Hz current (0.3 to 1.7 seconds) to join base metal up to 0.125 in. (3.2 mm) thick. Time up to 300 cycles (5 seconds) may be necessary on thicker materials to achieve adequate strength. The penetration, weld diameter, and reinforcement height generally increase with increased weld time.

6.2.4 Polarity. Most applications of gas metal arc spot welding employ direct current, electrode positive. Electrode negative can be used under special conditions when low penetration is required.

6.3 Joint Design. Gas metal arc spot welding may be used to weld lap joints in plain carbon steel, aluminum, magnesium, stainless steel, and copper-bearing alloys. Metals of the same or different thick-

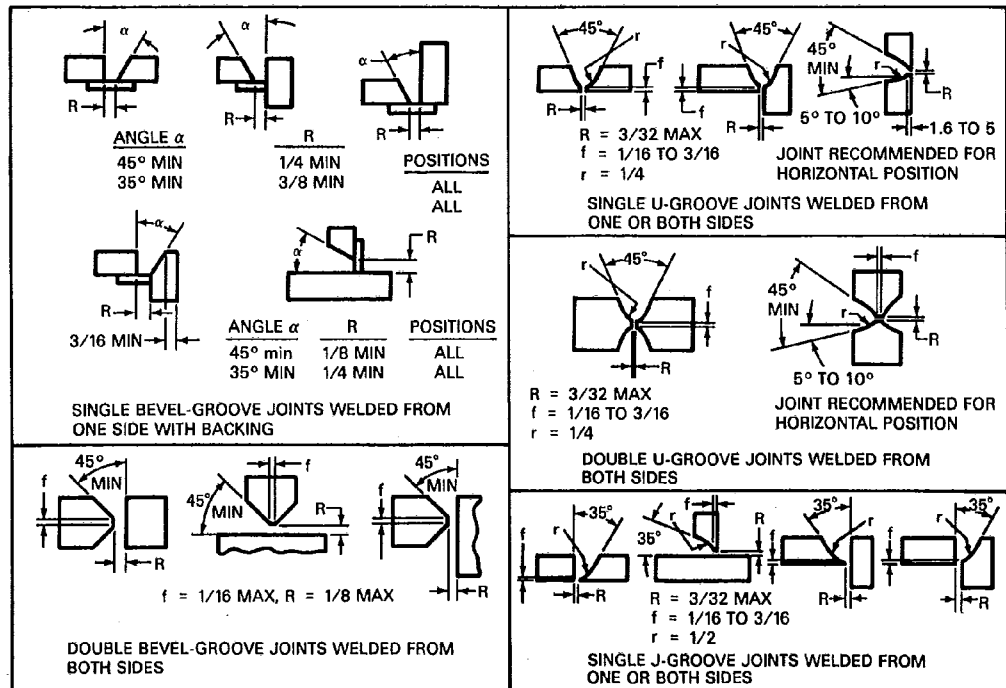


ALL DIMENSIONS IN INCHES EXCEPT ANGLES

SI EQUIVALENTS	
in.	mm
1/16	1.6
1/8	3.2
3/16	4.8
1/4	6.4

(A)

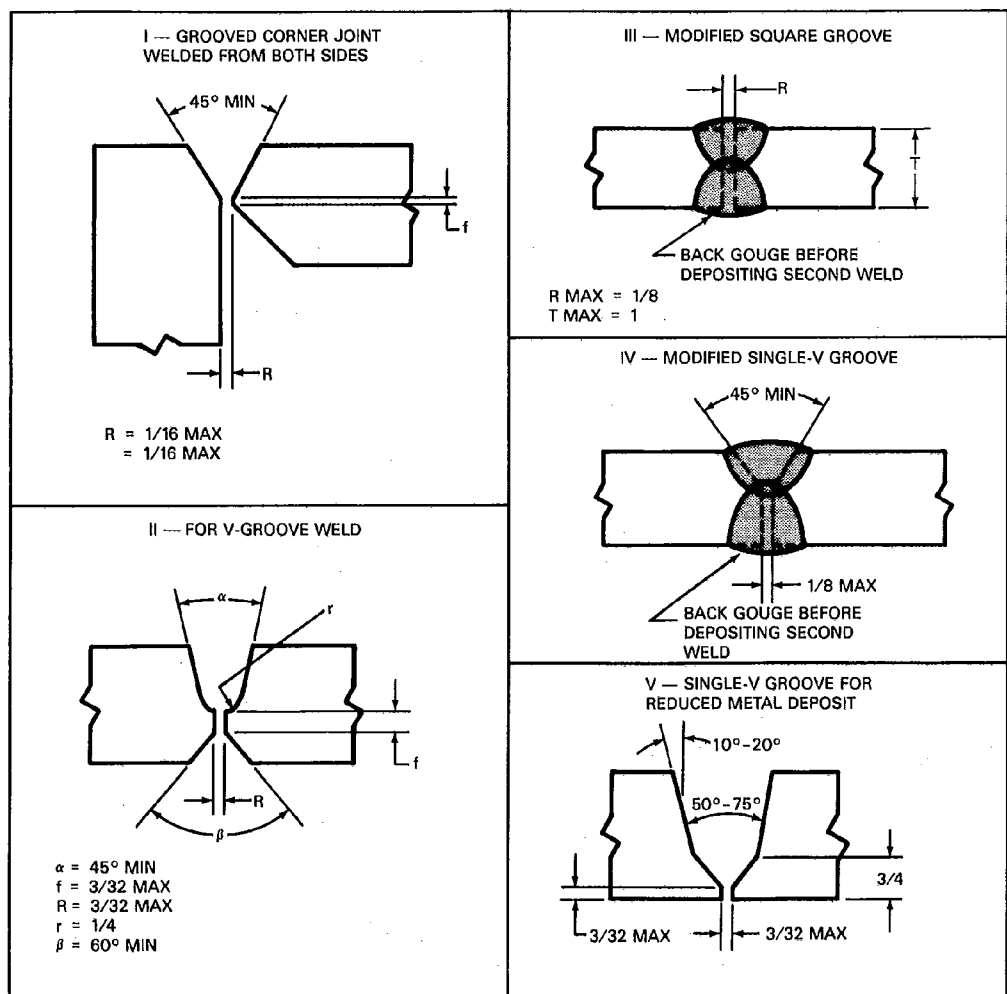
Figure 34 – Typical Weld Joint Design for GMAW (Steel)



ALL DIMENSIONS IN INCHES EXCEPT ANGLES

(B)

Figure 34 (Continued) – Typical Weld Joint Design for GMAW (Steel)

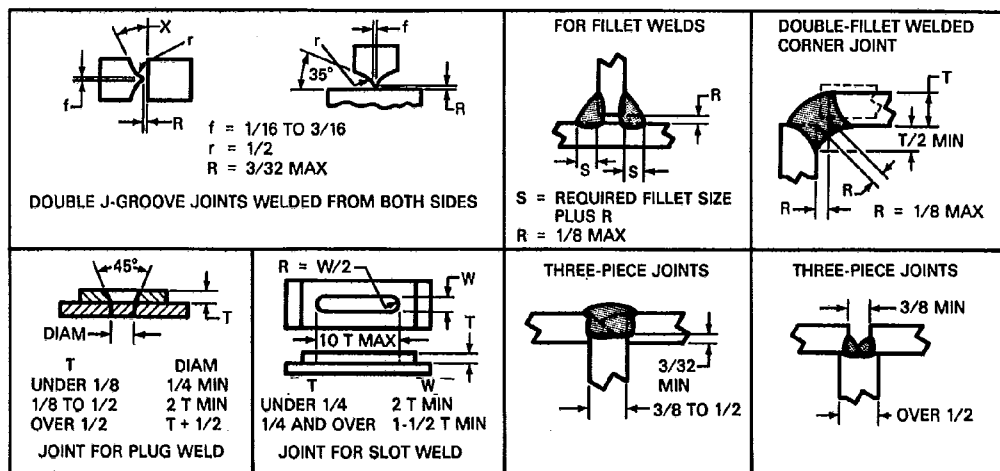


ALL DIMENSIONS IN INCHES EXCEPT ANGLES

(C)

SI EQUIVALENTS	
in.	mm
1/16	1.6
3/32	2.4
1/8	3.2
3/16	4.8
1/4	6.4
3/8	9.6
1/2	12.7
3/4	19.0
1	25.4

**Figure 34 (Continued) – Typical Weld Joint
Design for GMAW (Steel)**



ALL DIMENSIONS IN INCHES EXCEPT ANGLES

(D)

Figure 34 (Continued) – Typical Weld Joint Design for GMAW (Steel)

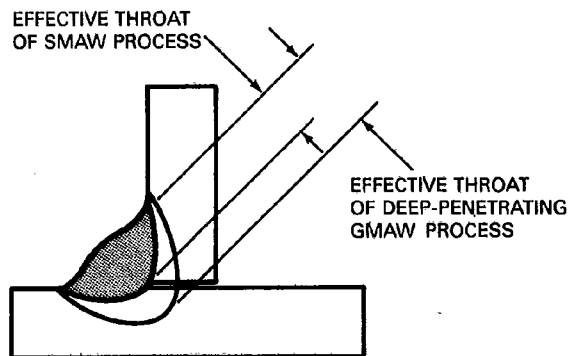


Figure 35 – Fillet Weld-Effective Throats

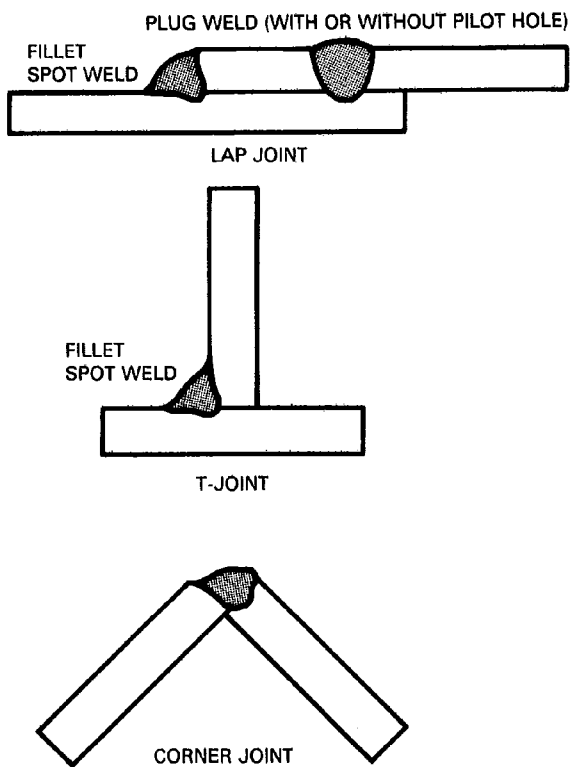


Figure 36 – Types of Joints for GMAW Spot Welding

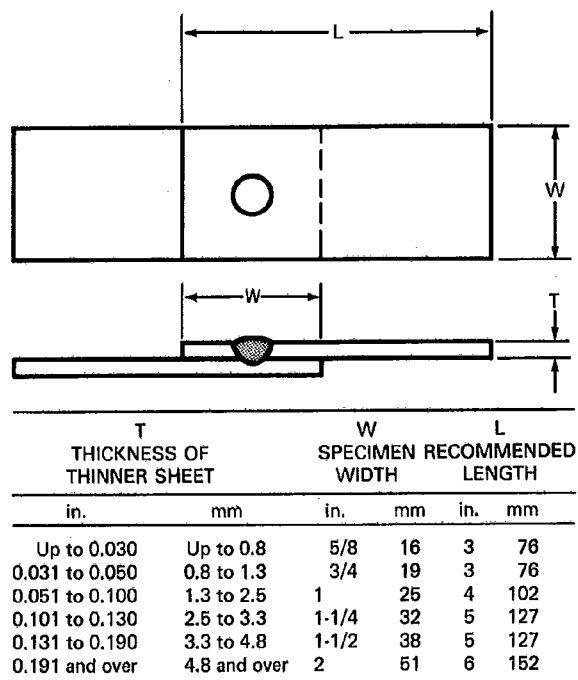


Figure 37 – Tension-Shear Test Specimen Dimensions

Table 8
GMAW Spot Welding of Plain Carbon Steel in the Flat Position
CO₂ Shielding Gas – 3/16 in. (4.8 mm) Diameter Nugget

Electrode Size		Gauge	Thickness		Arc Spot Time s	Electrode Consumed Per Spot		Current A (dcep)	Voltage V	Shear Strength Per Spot	
in.	mm		in.	mm		in.	mm			lb. force	kN
0.030	0.8	24	0.022	0.56	0.4	3-1/4	83	160	25	507	2.26
		22	0.032	0.81	0.6	8-1/4	210	190	27	1130	5.03
		20	0.037	0.94	0.8	12	305	190	27	1215	5.40
0.035	0.9	22	0.032	0.81	0.7	4-3/4	120	160	27	910	4.05
		20	0.037	0.94	0.8	5-1/8	130	160	27	1120	4.98
		18	0.039	0.99	0.9	9	229	200	28	1530	6.81
		16	0.059	1.50	1.0	14-1/2	368	240	30	2320	10.32
		14	0.072	1.83	1.5	20-3/4	527	240	30	3160	14.06
0.045 3/64	1.2	18	0.039	0.99	0.5	2-3/8	60	250	29	936	4.16
		16	0.059	1.50	1.0	5-3/4	146	250	29	2420	10.76
		14	0.072	1.83	0.8	6-5/8	168	300	30	2740	12.19
		12	0.110	2.79	0.8	10-1/4	260	350	32	3450	15.35
		11	0.124	3.2	1.0	13-1/2	343	350	32	4016	17.86
0.063 1/16	1.6	16	0.059	1.50	0.5	2-1/4	57	400	32	1673	7.44
		14	0.072	1.83	0.8	4	102	400	32	3308	14.71
		12	0.110	2.79	0.9	5-3/4	146	350	34	4340	19.31
		11	1/8	3.2	1.1	6-1/2	165	450	34	4960	22.06
			5/32	4.0	1.0	8	203	500	34	5286	23.51
			3/16	4.8	0.9	10-1/2	267	600	37	5573	24.79
			1/4	6.4	1.4	18-1/4	464	650	38	5986	26.63

Table 9
GMAW Spot Welding of Plain Carbon Steel in the Flat Position
CO₂ Shielding Gas - 1/4 in. (6.4 mm) Diameter Nugget

Electrode Size		Gauge	Thickness		Arc Spot Time s	Electrode Consumed Per Spot		Current A (deep)	Voltage V	Shear Strength Per Spot	
in.	mm		in.	mm		in.	mm			lb. force	kN
0.030	0.8	24	0.022	0.56	1	4-5/8	117	90	24	625	2.78
		22	0.032	0.81	1.2	5	127	120	27	730	3.25
		20	0.037	0.94	1.2	10-1/8	257	120	27	1337	5.95
0.035	0.9	22	0.032	0.81	1	6	152	140	26	800	3.56
		20	0.037	0.94	1	6	152	140	26	1147	5.10
		18	0.039	0.99	1	8-1/2	216	190	27	1507	6.70
		16	0.059	1.50	2	17-1/4	438	190	28	1434	6.38
		14	0.072	1.83	5	40-1/2	1029	190	28	2600	11.57
0.045 3/64	1.2	18	0.039	0.99	0.7	4	102	200	27	1414	6.29
		16	0.059	1.50	1	6	152	260	29	2070	9.21
		14	0.072	1.83	1.5	12-3/4	324	300	30	3224	14.34
		12	0.110	2.79	3.5	28-1/2	724	300	30	4300	19.13
		11	0.124	3.15	4.2	34	864	300	30	4114	18.30
0.063 1/16	1.6	16	0.059	1.50	1	2-3/4	70	250	29	1654	7.36
		14	0.072	1.83	1	5-1/2	140	360	31	3340	14.86
		12	0.110	2.79	1	7-1/4	184	440	32	5000	22.24
		11	1/8	3.15	1	8-1/2	216	490	32	5634	25.06
			5/32	4.0	1.5	9	229	490	32	5447	24.23
			3/16	4.8	2	16-3/4	425	490	32	6834	30.40
			1/4	6.4	3.5	28-1/8	714	490	34	8667	38.55

Table 10
GMAW Spot and Plug Welds on Aluminum
Argon Shielding Gas - 1/16 in. (1.6 mm) Diameter Electrode

Plate Thickness Top		Bottom		Preparation	Current A (dcep)	Voltage V	Weld Time s	Avg. Shear Strength		MIL-W-6860 Average Shear Strength	
in.	mm	in.	mm					lb. force	kN	lb. force	kN
0.040	1.0	0.040	1.0	Copper back	320	23-1/2	0.8	600	2.67	415	1.85
0.040	1.0	0.090	2.3	Copper back	330	23-1/2	1.0	660	2.94	415	1.85
0.050	1.3	0.050	1.3	Copper back	335	23-1/2	1.0	710	3.16	570	2.54
0.050	1.3	0.090	2.3	Copper back	350	23-1/2	1.2	900	4.00	570	2.54
0.050	1.3	0.125	3.2	None	240	23	2.0	1140	5.07	570	2.54
0.062	1.6	0.062	1.6	Copper back	340	23-1/2	1.2	1005	4.43	792	3.52
0.062	1.6	0.125	3.2	Copper back	350	23-1/2	1.5	1080	4.80	792	3.52
0.080	2.0	0.080	2.0	Copper back	375	24	1.4	1020	4.54	1137	5.06
0.080	2.0	0.125	3.2	Copper back	375	25	1.6	1180	5.25	1137	5.06
0.092	2.3	0.092	2.3	Refrasil*back	300	22	2.0	1135	5.05	1355	6.03
0.092	2.3	0.092	2.3	Plug 9.5 mm (3/8 in.) diam	170	26	2.5	990	4.40	1355	6.03
0.092	2.3	0.250	6.4	None	350	24	2.0	1640	7.29	1355	6.03
0.125	3.2	0.125	3.2	Refrasil*back	300	23	2.2	1600	7.12	2168	9.64
0.125	3.2	0.125	3.2	Plug 10.3 mm (13/32 in) diam	260	25	2.3	1340	5.96	2168	9.64
0.125	3.2	0.188	4.8	Copper back	400	24	2.3	1750	7.78	2168	9.64
0.250	6.4	0.500	12.7	Plug 11.1 mm (7/16 in.) diam	400	24	2.0	2120	9.43	Not Specified	
0.250	6.4	0.500	12.7	Plug 12.7 mm (1/2 in.) diam	370	25	2.5	3275	14.57	Not Specified	
0.156	4.0	0.156	4.0	Copper back plug 19mm(3/4 in.)	400	24-1/2	2.2	1720	7.65	Not Specified	
0.188	4.8	0.188	4.8	Copper back plug 10.3mm(13/32 in.)	410	25-1/2	2.6	1850	8.23	Not Specified	
0.188	4.8	0.125	3.2	Copper back plug 9.5mm(3/8 in.)	400	24-1/2	2.6	1610	7.16	Not Specified	

*Trade name, H.I. Thompson Co.

Table 11
Summary of Operating Conditions for GMAW Spot Welding of Various Gauges
of AZ31B (Magnesium) Sheet with AZ61A Electrode

Sheet Gauge				Electrode Diameter		Arc		Weld Time Hz	Range of Shear Strength Per Spot	
Top		Bottom								
in.	mm	in.	mm	in.	mm	Current A	Voltage V		lb. force	kN
0.040	1.0	0.090	2.3	0.040	1.0	175	22-26	30-70	40-1085	0.18-4.83
						200	24-26	25-50	760-1190	3.38-5.29
		0.125	3.2	0.040	1.0	175	22-26	40-100	310-1370	1.38-6.09
						200	22-28	20-90	460-1710	2.05-7.61
		0.190	4.8	0.040	1.0	175	22-26	40-100	50-1265	0.22-5.63
						200	22-28	20-100	360-1725	1.60-7.63
0.063	1.6	0.063	1.6	0.040	1.0	200	26	50-60	348-889	1.55-3.95
						0.090	2.3	0.040	1.0	200
		225	24-26	25-45	360-880	1.60-3.91				
		0.125	3.2	0.040	1.0	200	22-26	30-100	515-1165	2.29-5.18
						225	22-28	20-100	230-1340	1.02-5.96
		0.250	6.4	0.040	1.0	200	22-26	30-100	250-880	1.11-3.91
225	22-28	20-100				320-2000	1.42-8.90			
0.090	2.3	0.090	2.3	0.040	1.0	250	24-28	50-100	513-1129	2.28-5.02
						0.063	1.6	275	25-28	40-90
		0.125	3.2	0.063	1.6	275		22-26	30-100	520-1060
						300	24-28	25-80	230-960	1.02-4.27
		0.190	4.8	0.063	1.6	275	22-26	30-100	290-1145	1.29-5.09
						300	22-28	20-200	200-1700	0.89-7.56
0.125	3.2	0.125	3.2	0.094	2.4	325	24-27	40-100	583-1675	2.59-7.45
						350	24-25	40-100	680-1337	3.02-5.95
		0.156	4.0	0.094	2.4	350	22-26	30-100	530-1875	2.36-8.34
						375	24-26	30-80	640-1600	2.85-7.12
		0.190	4.8	0.094	2.4	350	22-24	30-100	190-1900	0.85-8.45
						375	24-28	30-100	270-1640	1.20-7.29
0.156	4.0	0.156	4.0	0.094	2.4	375	24-26	80-150	517-1437	2.30-6.39
0.190	4.8	0.190	4.8	0.094	2.4	375	24-26	80-150	782-1323	3.48-5.88
						400	24-26	60-110	853-1194	3.79-5.31

Table 12
GMAW Spot Welding of Stainless Steel to Plain Carbon Steel in the Flat Position

Electrode Size		Top Sheet		Bottom Sheet		Arc Spot Time s	Electrode Consumed Per Spot		Current A (dcep)	Voltage V
in.	mm	Material	Gauge	Thickness in. mm	Material	Thickness in. mm	in.	mm		
1/16	1.6	304	11	0.124 3.15	A36	2 50.8	2.0	11.25 ^a	286 ^a	400 33
1/16	1.6	304	11	0.124 3.15	A120	0.2 5.1	1.6	9.25 ^a	235 ^a	400 33
1/16	1.6	304	11	0.124 3.15	A36	2 50.8	2.0	11.25 ^b	286 ^b	450 31
1/16	1.6	304	11	0.124 3.15	A120	0.2 5.1	2.0	11.25 ^b	286 ^b	450 31
1/16	1.6	304	11	0.124 3.15	A36	0.25 6.4	1.6	10 ^c	254 ^c	400 28

a. 25cfh (11.8 liters per min) of CO₂, ER-308L HiSil filler metal.

b. 25cfh (11.8 liters per min) argon + 1% oxygen; ER-308L HiSil filler metal.

c. 30cfh (14.1 liters per min) of argon + 5% oxygen; ER-309 filler metal.

ness may be welded together. The thinner sheet should always be the top member when metals of different thickness are welded. Gas metal arc spot welding is normally restricted to the flat position. By modifying the nozzle design, gas metal arc spot welding is adaptable to lap-fillet joints (in the horizontal position), and corner joints (see Figure 36). A hole may be prepared in the top member on material too thick for burn-through welding. The weld is termed a *plug weld* in this case.

6.4 Tension-Shear Test. A test specimen obtained by lapping two strips of metal and joining them by a single spot weld is loaded in tension in a standard testing machine until the specimen ruptures. The dimensions on the test specimens are shown in Figure 37.

The ultimate tension-shear strength of the specimen and the manner of failure should be recorded; i.e., whether failure was by shear of the weld metal or by tear of the base metal, and whether a ductile or brittle fracture was obtained.

Because shear strength is proportional to the cross-sectional area of the weld deposit at the interface between the two sheets, the shear strength of a GMAW spot weld that joins sheets of a given thickness can be varied considerably by changing the controlled variables of current, arc volts, and arc time.

The strength of GMAW spot welds are in the same general range as resistance spot welds for the same thickness of material.

7. Inspection and Weld Quality

7.1 Introduction. Weld Quality control inspection procedures for GMAW joints are quite similar to those used for SMAW. Depending upon the applicable specifications, these procedures should provide for examination of the final weld product, determination of adequate welder or welding operator performance, and a satisfactory welding procedure.

Weld inspection on the assembled product is limited to the use of various nondestructive examination methods such as visual, liquid penetrant, magnetic particle, radiographic, and ultrasonic inspection. Destructive testing (tensile, shear, fatigue, impact, bend, fracture, peel, cross section, or hardness tests) is usually confined to engineering development, welding procedure qualification, and welder and welding operator performance qualifications tests. (Ref. ANSI/AWS B4.0, *Mechanical Testing of Welds*, latest edition)

7.2 Potential Problems

7.2.1 Hydrogen. Certain areas require particular attention to maintain process control. For example, an awareness of the potential problems of hydrogen embrittlement is important even though it is less likely to occur with GMAW since a hygroscopic flux or coating is not used. However, other hydrogen sources must be considered. The shielding gas must be sufficiently low in moisture content. This is normally well controlled by the gas supplier, but may have to be checked. Oil, grease, drawing compounds, etc., on the electrode or the base metal may also become potential sources for hydrogen pick-up in the weld metal.

Electrode manufacturers are aware of the need for cleanliness and take special care to provide a clean electrode. Contaminants are more likely to be introduced during handling in the user facility. The user who is aware of such possibilities may avoid serious problems, particularly in welding hardenable steels. The same awareness is necessary in welding aluminum, except that the potential problem is porosity caused by the relatively low solubility of hydrogen in solidified aluminum, rather than hydrogen embrittlement.

7.2.2 Oxygen and Nitrogen. Oxygen and nitrogen are potentially greater problems than hydrogen in the GMAW process. If the shielding gas is not completely inert or adequately protective, these elements may be readily absorbed from the atmosphere. The composition of welding electrodes is adjusted to provide adequate deoxidization elements to offset this tendency and avoid porosity to ensure sound deposits.

Even so, weld metal deposits made with GMAW in high-strength steels [150ksi (758MPa) yield strength] do not have as much ductility as those made with the gas tungsten arc welding (GTAW) process. Studies have also indicated that a gas shielding mixture of ninety eight percent argon and two percent oxygen or eighty percent argon and twenty percent CO₂ results in GMAW weld properties similar to those of the SMAW process. If the active component of the gas is increased (as in a fifty percent argon and fifty percent CO₂ mixture or one hundred percent CO₂) the impact strength of the resultant weld will be lower.

7.2.3 Cleanliness. Cleanliness in the use of bare electrodes in GMAW is more critical than with SMAW or submerged arc welding (SAW). The fluxing

compounds present in the SMAW and SAW shielding slag, scavenge and cleanse the molten weld deposit of oxides and gas-forming compounds. These fluxing slags are not normally present in GMAW, and thus, there may be a greater chance for porosity to form.

7.2.4 Incomplete Fusion. The reduced heat input common to the short circuiting mode of GMAW results in little melting of the base metal and a relatively cold weld. This is desirable on sheet metal and for out-of-position welding. However, an improper welding technique may cause incomplete fusion, in root areas or along groove faces.

7.3 Welding Discontinuities. Some of the more common weld discontinuities that may occur with the GMAW process are listed in the following paragraphs.

7.3.1 Undercutting (See Figure 38). The following are possible causes of undercutting and their corrective actions:

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Travel Speed too high	Use slower travel speed
(2) Welding voltage too high	Lower voltage
(3) Excessive welding currents	Reduce wire feed speed
(4) Insufficient dwell	Increase dwell at edge of molten weld puddle
(5) Gun Angle	Direct arc via gun angle so arc force can aid in metal placement.

7.3.2 Porosity. The following are possible causes of porosity and their corrective actions:

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Inadequate shielding gas coverage (see Figure 39)	Optimize the gas flow. Increase gas flow to displace all air from the weld zone; Decrease excessive gas flow to avoid turbulence and the entrapment of air in the weld zone. Remove spatter from nozzle. Eliminate any leaks in the gas line. Eliminate drafts

(from fans, open doors, etc.) blowing into the welding arc. Eliminate frozen (clogged) regulator in CO₂ welding by manifolding several cylinders or through the use of heaters. Use slower travel speed. Reduce nozzle-to-work distance. Hold gun at end of weld until molten metal solidifies.

- | | |
|--|--|
| (2) Gas contamination | Use welding grade shielding gas |
| (3) Electrode contamination | Use only clean and dry electrode |
| (4) Workpiece contamination | Remove all grease, oil, moisture, rust, paint, and dirt from work surface before welding. Use more highly deoxidizing electrode. |
| (5) Arc voltage too high (see Figure 40) | Reduce voltage. |
| (6) Excess contact tube-to-work distance | Reduce stick-out |

7.3.3 Incomplete Fusion. The following are possible causes of incomplete fusion and their corrective actions:

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Weld zone surfaces not free of film or excessive oxides	Clean all groove faces and weld zone surfaces of any mill scale impurities prior to welding.



Figure 38 – Undercutting at the Toe of the Weld

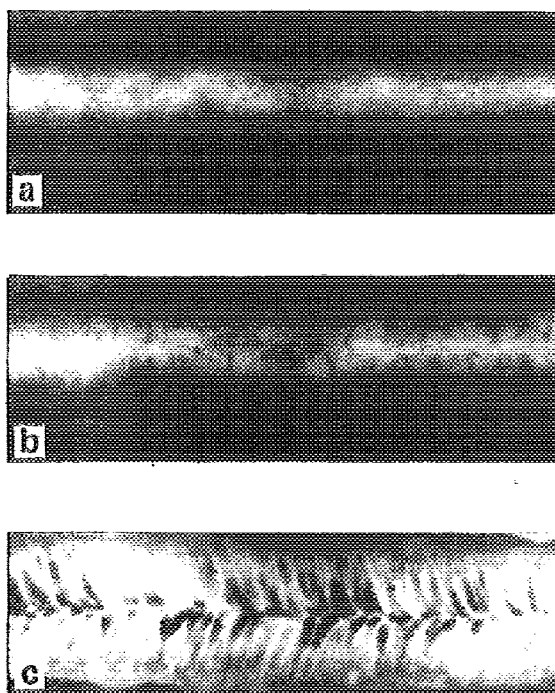


Figure 39 – Porosity Due to Inadequate Shielding Gas Coverage

- | | |
|---|---|
| (2) Insufficient heat input | Increase the wire feed speed and the arc voltage. Reduce electrode extension |
| (3) Too large a weld puddle | Minimize excessive weaving to produce a more controllable weld puddle. Increase the travel speed. |
| (4) Improper weld technique | When using a weaving technique dwell momentarily on the side walls of the groove. Provide improved access at root of joints. Keep electrode directed at the leading edge of the puddle. Provide proper transverse angulation. |
| (5) Improper joint design (see Figure 41) | Provide included angle of groove joint large enough to allow access to bottom of |

- (6) Excessive travel speed (see Figure 45)

the groove and side-walls with proper electrode extension and arc characteristics, or use a “J” or “U” groove.
Reduce travel speed

7.3.4 Incomplete Joint Penetration. The following are possible causes of incomplete joint penetration and their corrective actions:

- | <i>Possible Causes</i> | <i>Corrective Actions</i> |
|---|--|
| (1) Improper joint preparation | Joint preparation and design must be adequate to provide proper access to the bottom of the groove while maintaining proper electrode extension and arc characteristics. Reduce excessively large root face. Provide or increase the root gap in butt joints and increase depth of back gouge. |
| (2) Improper weld technique | Maintain electrode angle normal to work surface to achieve maximum penetration. Keep arc on leading edge of the puddle. |
| (3) Inadequate heat input (see Figure 42) | Increase the wire feed speed (welding current). Maintain proper electrode extension. |

7.3.5 Excessive Melt-Through. The following are possible causes of excessive melt-through and their corrective actions:

- | <i>Possible Causes</i> | <i>Corrective Actions</i> |
|--------------------------|---|
| (1) Excessive heat input | Reduce both wire feed speed (welding current) and accordingly the voltage. Increase the travel speed. |

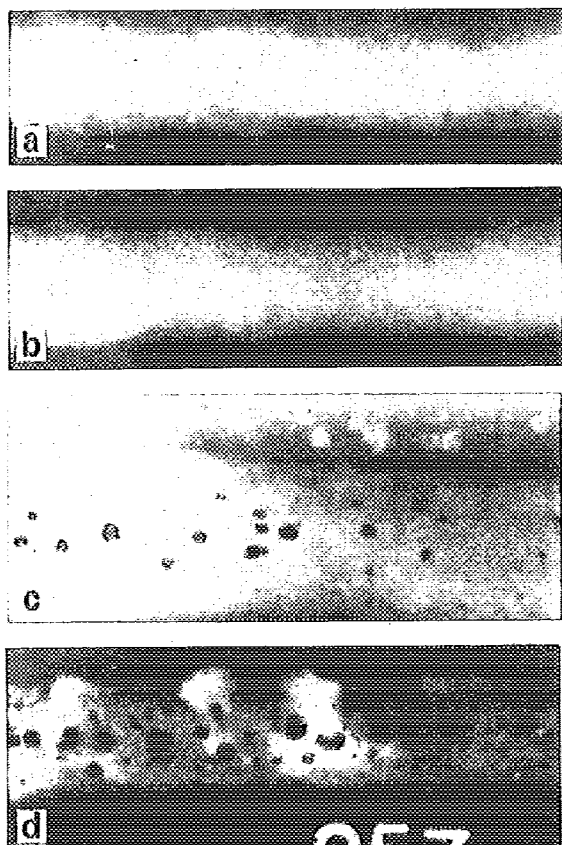


Figure 40 – Porosity Due to Excessive Voltage

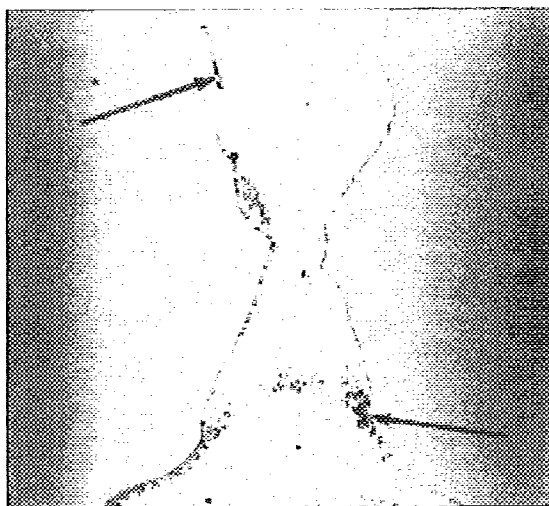


Figure 41 – Incomplete Fusion Due to Narrow Groove Preparation (5083 Aluminum Plate and ER5183 Filler Metal)

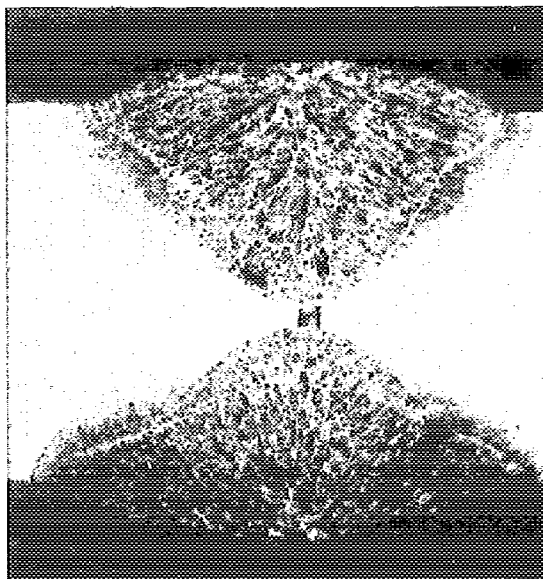


Figure 42 – Incomplete Root Penetration Due to Inadequate Welding Current

- (2) Improper joint penetration

Reduce excessive root opening.
Increase root face dimension.

7.3.6 Cracks. The following are possible causes of cracks and their corrective actions:

7.3.6.1 Weld Metal Cracks

- | <i>Possible Causes</i> | <i>Corrective Actions</i> |
|--|---|
| (1) Improper joint design | Maintain proper groove dimensions to allow deposition of adequate filler metal or weld cross section in order to overcome restraint conditions. |
| (2) Too high a weld depth-to-width ratio (see Figure 43) | Either increase arc voltage or decrease the current or both to widen the weld bead or decrease the penetration. Adjust the groove angle (joint preparation) |

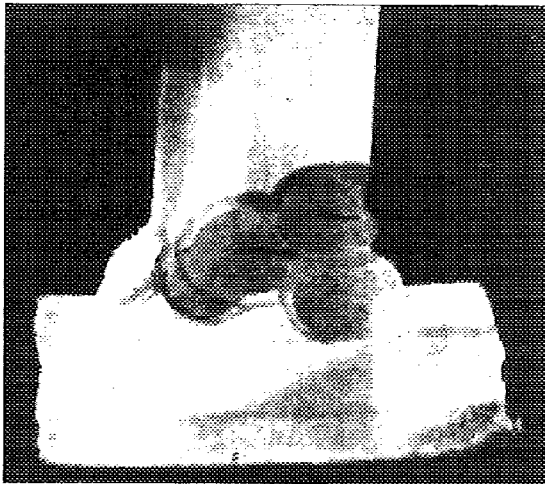


Figure 43 – Weld Metal Cracking Due to Excessive Depth-to-Width Ratio

- | | |
|---|---|
| (3) Too small a weld bead (particularly fillet and root beads) | Decrease travel speed to increase cross section of deposit. |
| (4) Heat input too high causing excessive shrinkage and distortion. | Reduce either current or voltage, or both. Increase travel speed. |
| (5) Hot-shortness | Use ferrous electrode with sufficient manganese (use shorter arc length to minimize loss of manganese across the arc). Adjust the groove angle (joint preparation) to allow adequate percentage of filler metal addition. Adjust pass deposition sequence to reduce restraint on weld during cooling. Change to another filler metal providing desired characteristics. |
| (6) High restraint of the joint members | Use preheat to reduce magnitude of residual stresses. Adjust welding sequence to reduce restraint conditions. |

- (7) Rapid cooling in the crater at the cooling rate (see Figure 44)

Use a tapered power control to reduce the end of a weld. Fill craters adequately.

7.3.6.2 Heat-Affected Zone Cracks (almost always associated with hardenable steels)

Possible Causes	Corrective Actions
(1) Hardening in the heat-affected zone	Preheat to retard cooling rate.
(2) Residual stresses too high	Use stress relief heat treatment.
(3) Hydrogen embrittlement	Use clean electrode shielding. Use dry shielding gas. Remove contaminants from the base metal. Hold weld at elevated temperatures for several hours before cooling (temperature and time required to diffuse hydrogen are dependent on base metal type).

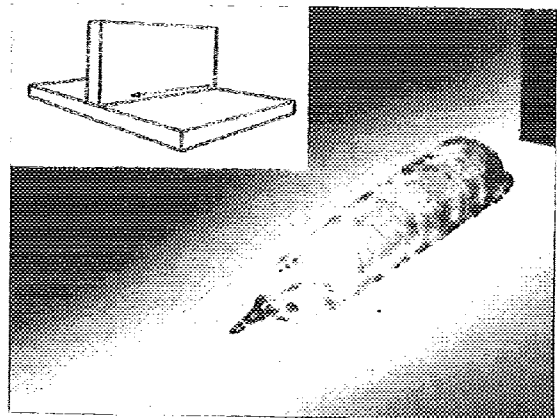


Figure 44 – Weld Metal Cracking in Crater at End of Weld

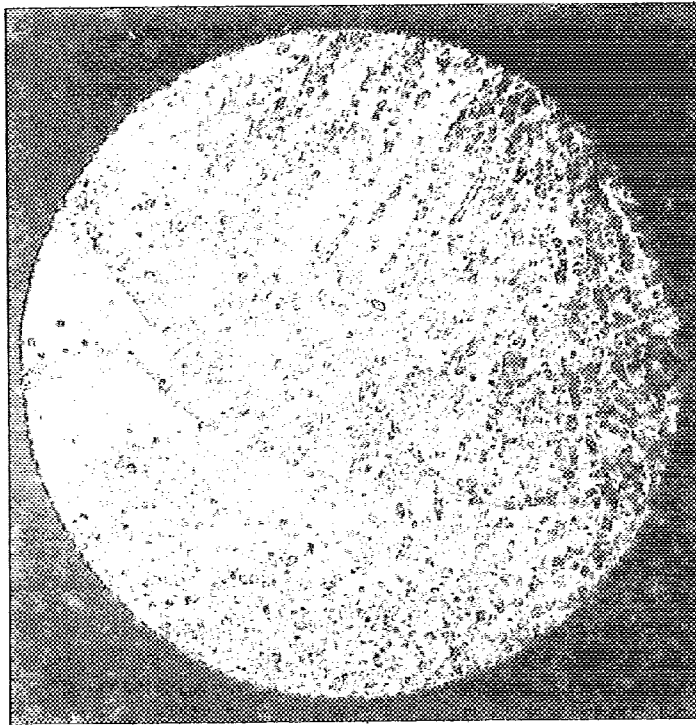


Figure 45 – Incomplete Fusion Due to Excessive Travel Speed

7.3.6.3 General Cracks

Possible Causes

- (1) Presence of notches or points of high stress concentrations

Corrective Actions

Avoid undercutting.
Limit reinforcements.
Maintain maximum reentrant angle of reinforcement at toe of weld.
Provide adequate root penetration.

7.3.7 Inclusions. The following are possible causes of inclusions and their corrective actions:

7.3.7.1 Non-Metallic Inclusion

Possible Causes

- (1) Multipass, short circuit arc welding

Corrective Actions

Remove glassy slag islands from weld deposits before making subsequent passes

7.3.7.2 Film Type Inclusion

Possible Causes

- (1) High Travel Speeds

Corrective Actions

Reduce travel speed.
Use more highly deoxidized electrode.
Increase arc voltage.

7.3.8 Irregular Weld Shape. The following are possible causes of irregular weld shape and their corrective actions:

7.3.8.1 Waviness of the Weld Bead (see Figure 46)

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Excessive electrode extension	Reduce electrode extension.
(2) Hard electrode with small cast (small radius of curvature).	Use straightening rolls.

7.3.8.2 Overlap or Sagging

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Welding out-of flat position in spray type transfer (see Figure 47)	Weld in the flat position, especially with high currents. Increase travel speed. Adjust gun angle. Increase the arc voltage.
(2) Weld too narrow for the amount of reinforcement (see Figure 48)	

7.3.8.3 Humping (see Figure 49)

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Excessive travel speed	Reduce travel speed.

7.3.8.4 Spatter

<i>Possible Causes</i>	<i>Corrective Actions</i>
(1) Shorting of the electrode and droplet to the work	Raise the arc voltage. Limit the rate of current rise by increasing inductive reactance in the welding circuit (short circuiting transfer).
(2) Excessive spatter when using CO ₂ gas shielding	Decrease arc voltage, or increase electrode feed speed to "bury" the arc and thus contain the spatter.
(3) Welding in globular transfer range (argon shield)	Increase current to an axial spray transfer range

7.3.9 Unmelted Electrode on Root Side ("Whiskers"). The following is a possible cause of unmelted electrode on root side and its corrective actions:

Possible Causes

- (1) Improper weld technique

Corrective Actions

Reduce the travel speed.
Use weaving motion.
Increase stick-out distance.
Decrease wire feed speed.

8. Training

Maximum benefits from GMAW may be derived by introducing the process through a well-planned and extensive training program that should include not only the welders and welding operators, but also key supporting personnel such as top management and those responsible for supervision, engineering and maintenance, and inspection.

A suggested program format follows.

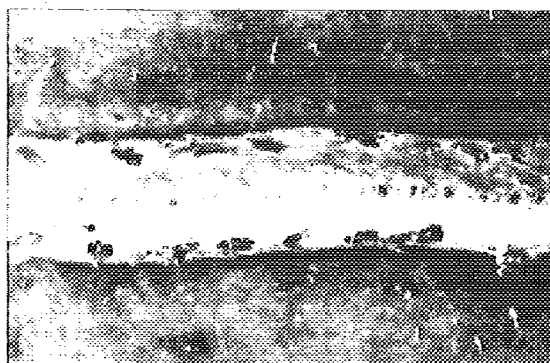


Figure 46 – Weld Bead Waviness

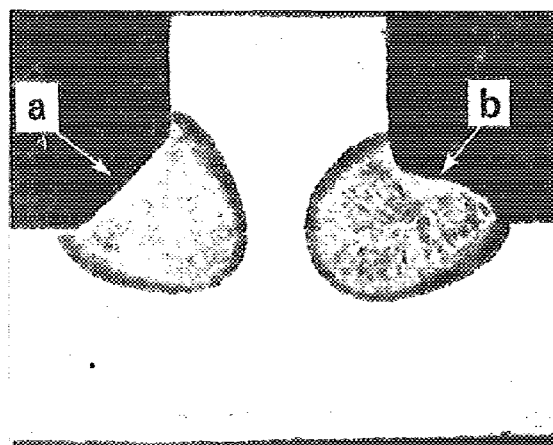


Figure 47 – Sagging of Weld Bead Due to Position of Welding

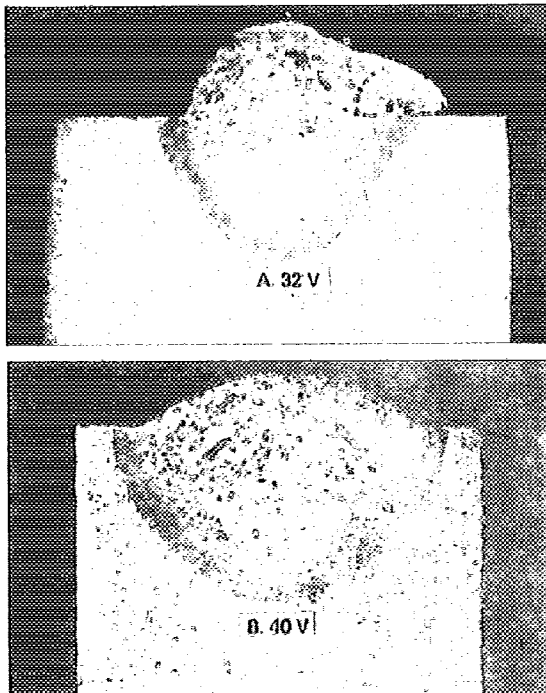


Figure 48 – Overlap of Weld Bead Due to Incorrect Voltage

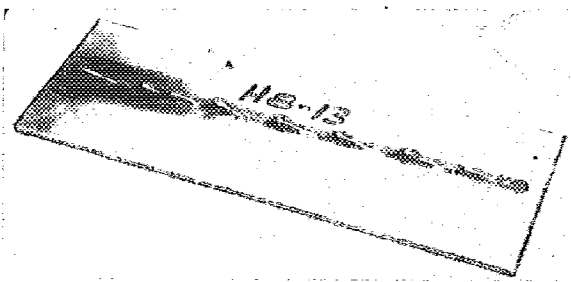


Figure 49 – Humping of Weld Metal Due to Excessive Travel Speed

8.1 Introductory Training Program on Steel. A training program has been adopted for many situations in which GMAW is used to produce industrial, automotive, and agricultural equipment and similar metal articles. An outline of this training program is as follows:

- (1) The GMAW Process-Discussion-and Demonstration
- (2) The GMAW Equipment-Discussion and Demonstration
- (3) Demonstration and Practice

- (4) Making Fillet Welds on Sheet Metal-All Position
- (5) Welding with Various Settings-Readjusting-Practice
- (6) Welding of Misaligned Materials-Practice-Tests

This program could probably be reduced for routine jobs of a repetitive nature. On-the-job training can supplement this program and substitute for some of the practice periods.

However, someone who has had adequate training with this equipment and process should supervise to correct techniques and other operational errors during the learning period.

8.2 Welding Nonferrous Metals. This training program should be undertaken after the completion of the Introductory Training Program to allow familiarization with the process and process equipment for making welds on steel. A specific program should be initiated for each nonferrous metal involved. The program should present and explain:

- (1) The specific properties and peculiarities of the metal involved
- (2) The types, alloys, composition, and specification system for the particular metal involved
- (3) The selection of filler metal and shielding gas to match the base metal
- (4) Additional precautions such as special cleaning, special shielding, special postweld treatment, etc.
- (5) Any special equipment variations

The program should proceed as follows:

- (1) Make fillet welds on sheet metal-all positions, demonstration and practice
- (2) Welding with various settings on various metal thicknesses-readjusting-practice
- (3) Testing-qualification if required

8.3 GMAW Course for Steel Pipe. Pipe welding usually involves fixed position welding; i.e., welding without rotating the pipe. The following is an example of a pipe welding training program for steel pipe.

- (1) GMAW Process-Discussion and Demonstration
- (2) GMAW Equipment-Discussion and Demonstration
- (3) Fillet Welds on Sheet Metal-All Position-Demonstration and Practice
- (4) Butt Welds-Square Groove-All Position-Demonstration and Practice
- (5) Welding with Various Equipment Settings-Readjustments-Practice

- (6) Pipe Welding-Root Pass-5G Horizontal Fixed Position (Weld in Flat, Vertical, and Overhead Positions) and the 6G inclined Fixed Position
 - (7) Making Complete Welds-5G Horizontal Fixed Position (Weld in Flat, Vertical, and Overhead Positions)
 - (8) Making Root Pass in 2G Vertical Position (Weld Horizontal)
 - (9) Welding Pipe in 2G Vertical Position (Weld Horizontal)
 - (10) Practice and Simulated Qualification Tests
- Welder training is very important! Welding defects have been traced to improper welding procedures and welding techniques. Proper training and supervised practice by a qualified welding instructor will improve welding quality.

8.4 GMAW Equipment Maintenance and Trouble-Shooting Course. Semi-automatic and automatic welding equipment are more complex than the single operator welding machine used in the past. The growing need for personnel trained in the maintenance and trouble-shooting of all types of welding equipment is greatest for those trained for newer, more complex types. The course outlined here is designed to train repair personnel for the maintenance and trouble-shooting of GMAW equipment. It would apply to all types of semiautomatic gas-shielded welding equipment. Personnel selected for this course should have good mechanical background, a knowledge of basic electricity, and a knowledge of welding, preferably with welding experience. The maintenance course should cover the following:

- (1) Review of Basic Electricity
- (2) Test Instruments and Reading of Schematics
- (3) GMAW Equipment and Operations
- (4) Typical Welding Problems and Causes
- (5) Principals of Trouble-shooting
- (6) Electrode Feeders-Maintenance and Trouble-shooting
- (7) Gun and Cable Assemblies-Maintenance and Trouble-shooting
- (8) Rotating Power Sources-Maintenance and Trouble-shooting
- (9) Static Type Power Sources-Maintenance and Trouble-shooting
- (10) Complete GMAW Package-Trouble-shooting

Operating manual covering each piece of equipment involved in the GMAW process (available from the equipment manufacturer) could provide

the essential text material for this part of the course.

9. Qualification

9.1 Introduction. General methods for procedure, welder, and welding operator qualifications are detailed in the latest edition of ANSI/AWS B2.1, *Welding Procedure and Performance Qualification*. The following include a number of specifications that now incorporate consideration for the GMAW process.

ANSI/AWS D1.1, Structural Welding Code-Steel
ANSI/AWS D1.3, Structural Welding Code-Sheet Steel

ANSI/AWS D5.2, Standard for Welded Steel Elevated Tanks, Standpipes, and Reservoirs for Water Storage

ANSI/AWS D10.9, Standard for Qualification of Welding Procedures and Welders for Piping and Tubing

ANSI/AWS D14.1, Specification for Welding Industrial and Mill Cranes

ANSI/AWS D14.2, Specification for Metal Cutting Machine Tool Weldments

ANSI/AWS D14.3, Specification for Welding Earthmoving and Construction Equipment

ASME Boiler and Pressure Vessel Code, Section IX, Welding and Brazing Qualifications

American Petroleum Institute, Standard 1104 Marine Engineering Regulations and Material Specifications (CG 115)

ANSI B96.1, Specification for Welded Aluminum Alloy Field-Erected Storage Tanks

Some generalized criteria for guidance in qualification basics for the GMAW process are presented in the following paragraphs.

9.2 General. In considering qualification, the broad versatility range of GMAW (defined basically by the variables of mode of weld metal transfer and type of shielding gas) must be taken into account.

It is assumed that welding conditions will be selected for operating within the optimum range of the process and that filler metals will be judiciously selected. Guidelines for both welding procedures and the selection of filler materials and shielding gases are presented within section 4 of this document; section 5 provides a basic guide for joint design. The filler metal specifications referenced specify minimum mechanical properties based upon undiluted weld metal and chemistry based on electrode composition.

Depending on the welding process used, the final properties of the weld metal will be influenced by dilution and some loss in elements in transferring across the arc, plus a potential change in chemistry due to metallurgical reactions within the weld puddle (deoxidation and oxidation), and shielding gas reactions. The extent of the interactions which occur across the arc and within the weld puddle is dependent upon the mode of arc transfer, the base metal chemistry, joint design, energy input, and the shielding gas.

These interactions provide a basic approach to the selection of filler metal best suited for an application. However, practicality dictates that the engineer must rely on welding test data and past experience to qualify a welding procedure for a given application.

9.3 Procedure Qualification. Procedure qualification assures the proper matching of the weld metal to the base metal properties in conjunction with adequate heat-affected zone properties. It also establishes the versatility or conformance of the welding process (i.e., adaptability of the process to performance under fabrication conditions such as environment and positioning). Welder and welding operator qualifications confirm the skill of the welder or welding operator and their ability to follow the directions of the written welding procedure.

In general, procedure qualification is based on the following basic criteria in matching the weld metal to the base metal properties:

- (1) Chemistry
- (2) Strength (ultimate tensile or yield strength or both)
 - (a) Groove weld – will require a close matching of these properties in order to achieve 100 percent joint efficiency
 - (b) Fillet Weld – a close matching of these properties may not be necessary, as it may be possible to deposit a larger cross section (a larger fillet than required by design) to compensate for lower strength.
- (3) Ductility
- (4) Toughness

Qualification of the procedure may require additional consideration to cover areas such as subsequent heat treatment operations, corrosion resistance, wear resistance, color match, etc.

9.4 Variables. The two most important variables responsible for unique physical variations in the weld deposit in GMAW are the mode of metal trans-

fer and the shielding gas. With respect to qualification, these two variables are responsible for resultant weld physical characteristics such as:

- (1) Shape and appearance of weld reinforcement
- (2) Fusion characteristics (and weld bead profile)
 - Example of Workmanship Samples
- (3) Penetration
- (4) Spatter level

These characteristics are very important considerations in the process choice and for subsequent successful qualification.

9.5 Types of Tests. Qualification of a welding process or welder or welding operator for a specific area of application may be judged by a produced physical example. Basic specimens which might be chosen as part of the qualification requirements are listed in the following paragraphs as typical examples. These basic tests are illustrated in Figures 50 through 63. Test procedures and methods of determining the mechanical properties are detailed in the latest edition of ANSI/AWS B4.0, *Standard Methods for Mechanical Testing of Welds*. Additional information on qualification may be found in the latest edition of ANSI/AWS B2.1, *Welding Procedure and Performance Qualification*.

Note that welds encountered in actual construction must be classified as being flat, horizontal, vertical, or overhead, in accordance with the definitions given in Figures 64 and 65. Also note that all mechanical specimens are generally applicable to process qualifications, but only those tests applying to soundness or workmanship are used to judge welder or welding operator qualification. Welding symbols in these figures are in accordance with ANSI/AWS A2.4-86, *Symbols for Welding, Brazing, and Nondestructive Examination*.

9.5.1 The following are tests for fillet welds:

- (1) Workmanship Samples (for quality or manner of work) designed to provide an example of the actual production application.
- (2) Fillet Weld Break Test (for porosity and lack of fusion)
- (3) Longitudinal or Transverse Shear Test (for shear strength)
- (4) Fillet Weld Soundness Test-Free Bend Specimen (for ductility)
- (5) Fillet Weld Soundness Test-Guided Root Bend Specimen (for soundness).

9.5.2 The following are tests for groove welds:

- (1) Workmanship Samples (for quality or man-

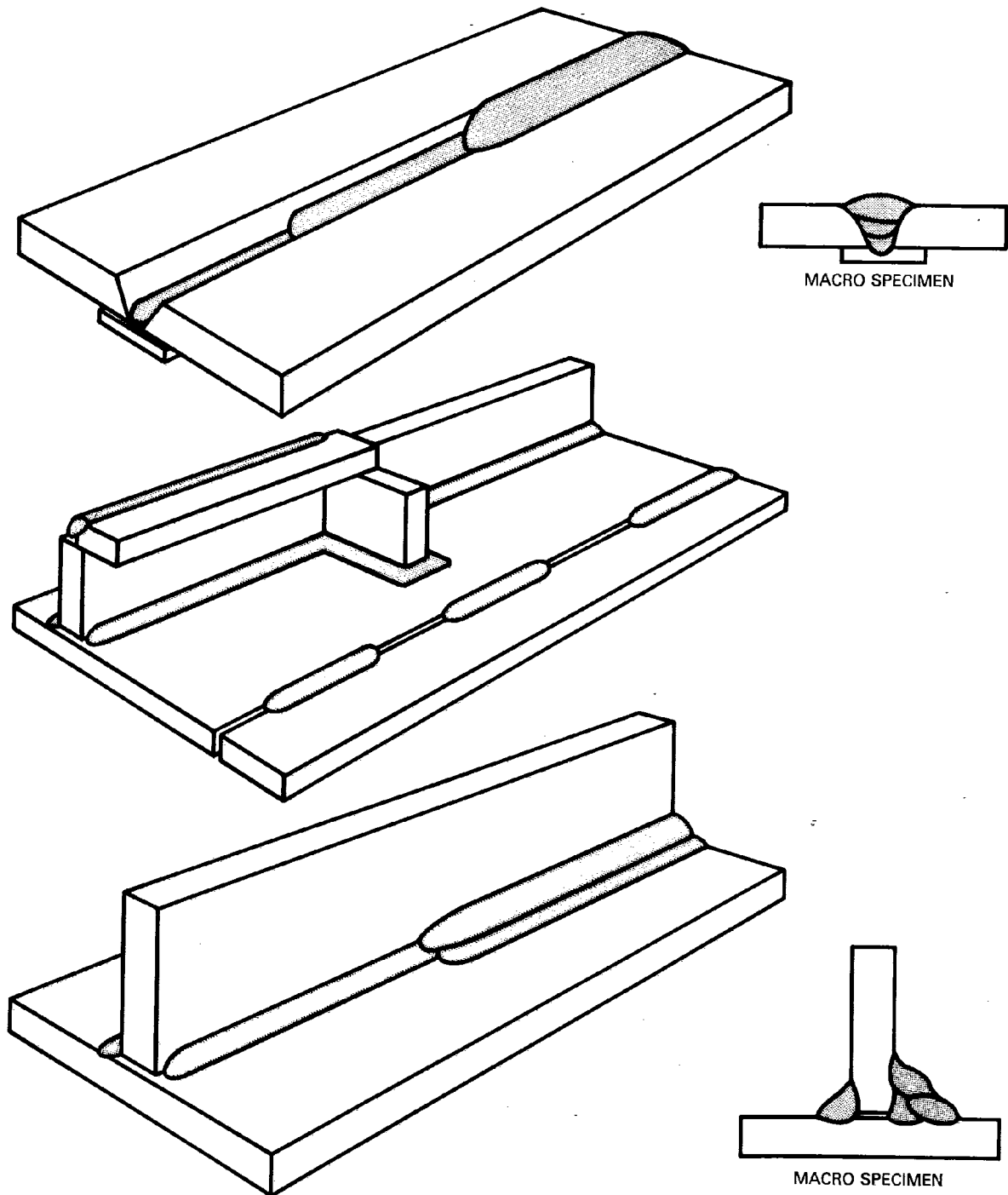


Figure 50 – Example of Workmanship Samples

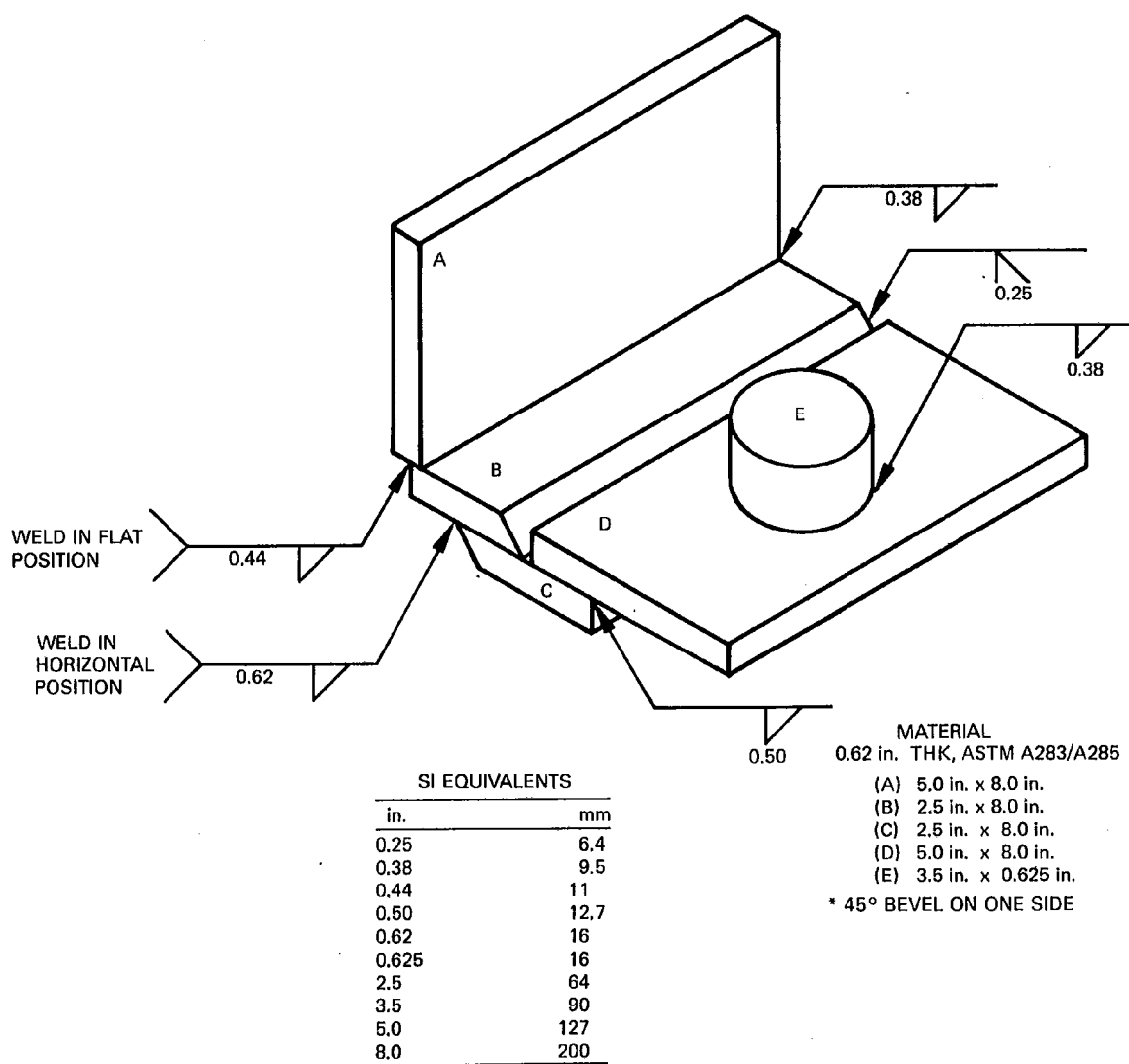
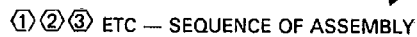


Figure 51 – Example of Workmanship Sample



(A)	2.0 STANDARD BLACK PIPE 4.0 LONG	
(B)	2.0 STANDARD BLACK PIPE 6.0 LONG	
(C)	1.5 STANDARD BLACK PIPE 4.0 LONG	
(D)	0.38 x 5.0 x 6.0 LONG	A283/A285
(E)	0.38 x 5.0 x 6.0 LONG (45° BEVEL)	A242
(F)	0.75 x 6.0 x 6.0 LONG	A516
(G)	0.25 x 1.0 x 6.0 LONG	A36

SI EQUIVALENTS

in.	mm
0.06	1.5
0.12	3.2
0.16	4
0.25	6.4
0.38	9.5
0.50	12.7
0.75	19
1.0	25
1.5	38
2.0	51
4.0	102
5.0	127
6.0	153

Figure 52 – Workmanship Specimens

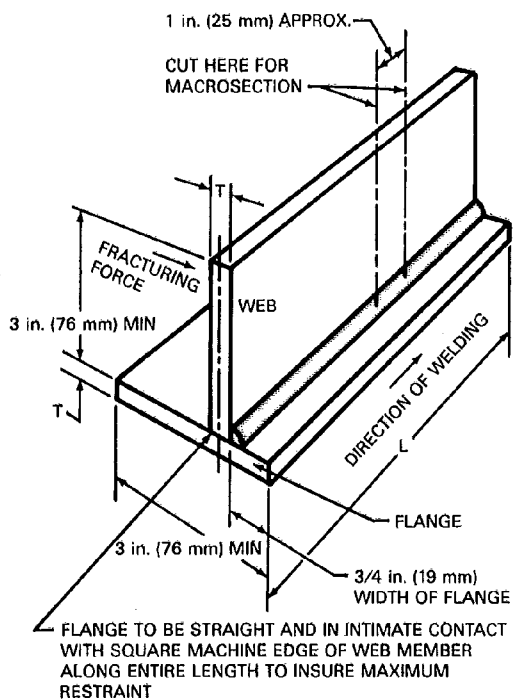


Figure 53 – Preparation of Fillet Weld Break Test Specimen

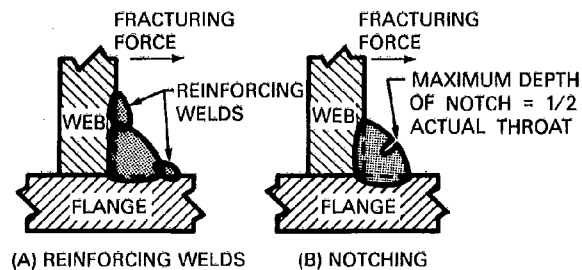
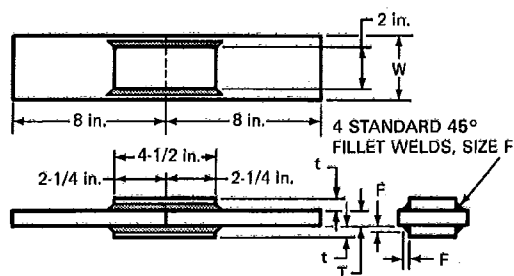


Figure 54 – Methods for Facilitating Fillet Weld Fracture



SI EQUIVALENTS

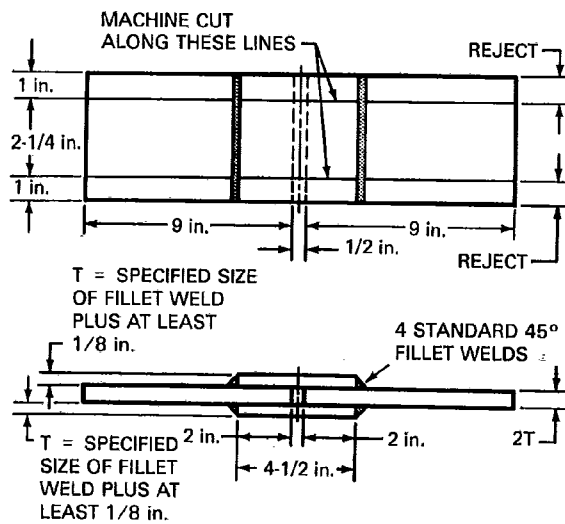
in.	mm
1/8	3.2
1/4	6.4
3/8	9.6
1/2	12.7
3/4	19
1	25
1-1/4	32
2	51
2-1/4	57
3	76
3-1/2	89
4-1/2	114
8	203

DIMENSIONS

	in.	in.	in.	in.
SIZE OF WELD F	1/8	1/4	3/8	1/2
THICKNESS t	3/8	1/2	3/4	1
THICKNESS T	3/8	3/4	1	1-1/4
WIDTH W	3	3	3	3-1/2

NOTE: ALL DIMENSIONS ARE IN INCHES

Figure 55 – Longitudinal Fillet Weld Shearing Specimen After Welding



SI EQUIVALENTS

in.	mm
1/8	3.2
1/2	12.7
1	25
2	51
2-1/4	57
4-1/2	114
9	229

NOTE: ALL DIMENSIONS ARE IN INCHES

DIMENSIONS SHOULD BE ALTERED TO ALLOW FOR PENETRATION CAPABILITIES OF THE PROCESS FOR BOTH THE LONGITUDINAL AND THE TRANSVERSE FILLET WELD SHEAR SPECIMEN (SEE SECTION 5).

Figure 56 – Transverse Fillet Weld Shearing Specimen

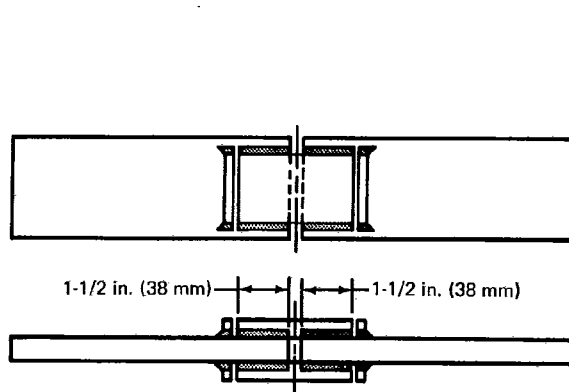


Figure 57 – Longitudinal Fillet Weld Specimen After Machining

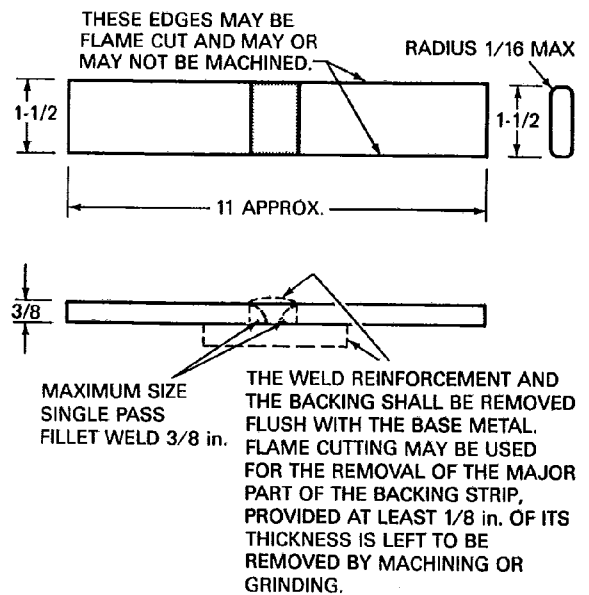
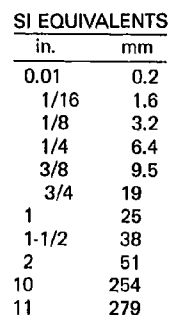
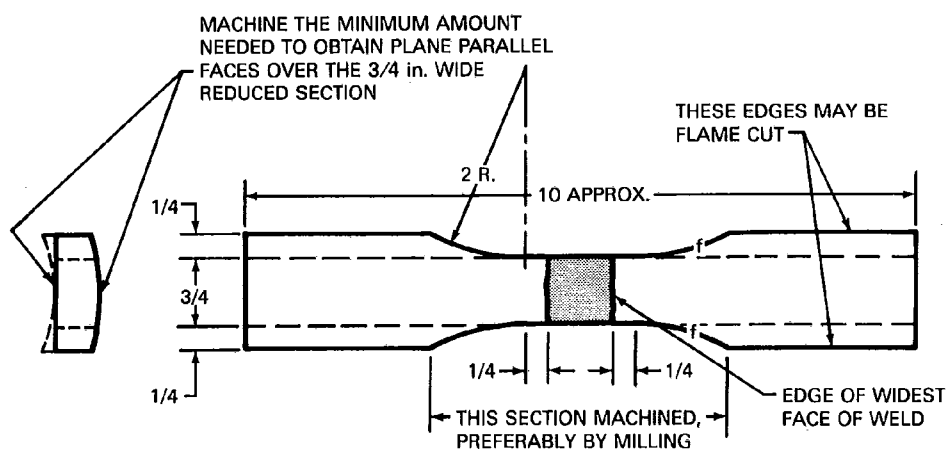


Figure 58 – Fillet Weld-Soundness Test Specimens



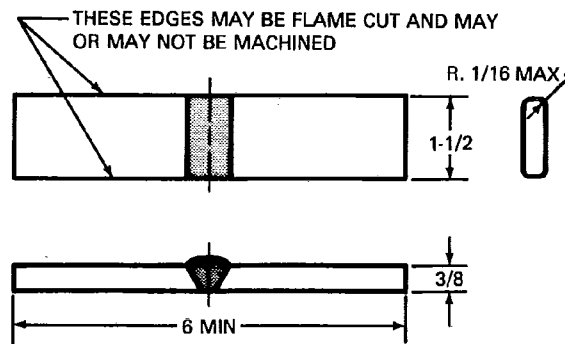
NOTE: ALL DIMENSIONS ARE IN INCHES.

Figure 59 – Reduced-Section Tension Specimen (Plate)



NOTE: ALL DIMENSIONS ARE IN INCHES.

Figure 60 – Reduced-Section Tension Specimen (Pipe)



NOTE: WELD REINFORCEMENT AND BACKING STRIP, IF ANY SHALL BE REMOVED FLUSH WITH THE SURFACE OF THE SPECIMEN. IF A RECESSED STRIP IS USED THIS SURFACE OF THE SPECIMEN MAY BE MACHINED TO A DEPTH NOT EXCEEDING THE DEPTH OF THE RECESS TO REMOVE THE STRIP, EXCEPT THAT IN SUCH CASES THE THICKNESS OF THE FINISHED SPECIMEN SHALL BE THAT SPECIFIED ABOVE.

NOTE: ALL DIMENSIONS ARE IN INCHES.

Figure 61 – Face- and Root-Bend Specimen (Plate)

NOTE: WELD REINFORCEMENT AND BACKING STRIP, IF ANY SHALL BE REMOVED FLUSH WITH THE SURFACE OF THE SPECIMEN. IF A RECESSED RING IS USED, THIS SURFACE OF THE SPECIMEN MAY BE MACHINED TO A DEPTH NOT EXCEEDING THE DEPTH OF THE RECESS TO REMOVE THE RING, EXCEPT THAT IN SUCH CASES THE FINISHED SPECIMEN SHALL BE THAT SPECIFIED ABOVE.

NOTE: ALL DIMENSIONS ARE IN INCHES.

SI EQUIVALENTS

in.	mm
1/16	1.6
1/8	3.2
3/8	9.5
1-1/2	38
2-3/4	69
6	152

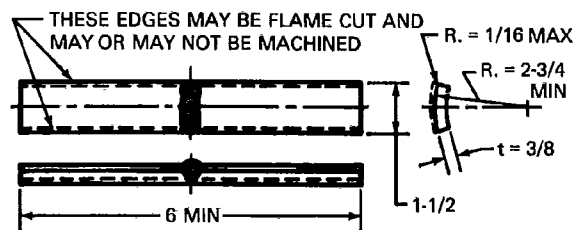
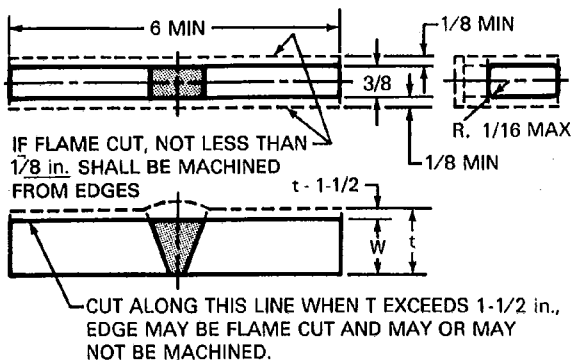


Figure 62 – Face- and Root-Bend Specimen (Pipe)



t, in.	W, in.	t, mm	W, mm
3/4 to 1-1/2	t	19 to 38	t
>1-1/2	1-1/2	38	38

NOTE: ALL DIMENSIONS ARE IN INCHES.

Figure 63 – Side-Bend Specimen

ner of work) designed to provide an example of the actual production application.

- (2) Reduced Section Tension Test (for tensile strength)
- (3) Free Bend Test (for ductility)
- (4) Root Bend Test (for soundness)
- (5) Face Bend Test (for soundness)
- (6) Side Bend Test (for soundness)

9.5.3 Test for All Welds. Prototype structures built to welding procedures based upon previous production experience are advantageous in some applications. These structures are then field tested under actual service conditions or under accelerated laboratory testing to provide a correlation between the welding procedure and the actual service requirements.

10. Recommended Safe Practices

10.1 Scope. These recommended safe practices are for use with the gas metal arc welding processes only. They are designed to protect personnel from injury and illness and to guard against property damage.

10.1.1 For detailed safety information, refer to the manufacturer's instructions and the latest edition of ANSI/ASC Z49.1, *Safety in Welding and Cutting* (published by American Welding Society). For mandatory Federal safety regulations established by the U. S. Labor Department's Occupational Safety and Health Administration (OSHA), refer to the latest edition of OSHA standards *Code*

of Federal Regulations, Title 29 CFR 1910 (General Industry) available from the Superintendent of Documents, U. S. Printing Office, Washington, D. C. 20402.

Other standards may also apply such as 29 CFR 1915 for use in shipyard fabrication.

10.1.2 This document addresses potential hazards associated with the gas metal arc welding processes. No attempt has been made to include all hazards resulting from misapplication of the process.

10.1.3 The following potential hazards are considered to be of sufficient magnitude to be included within the scope of this document.

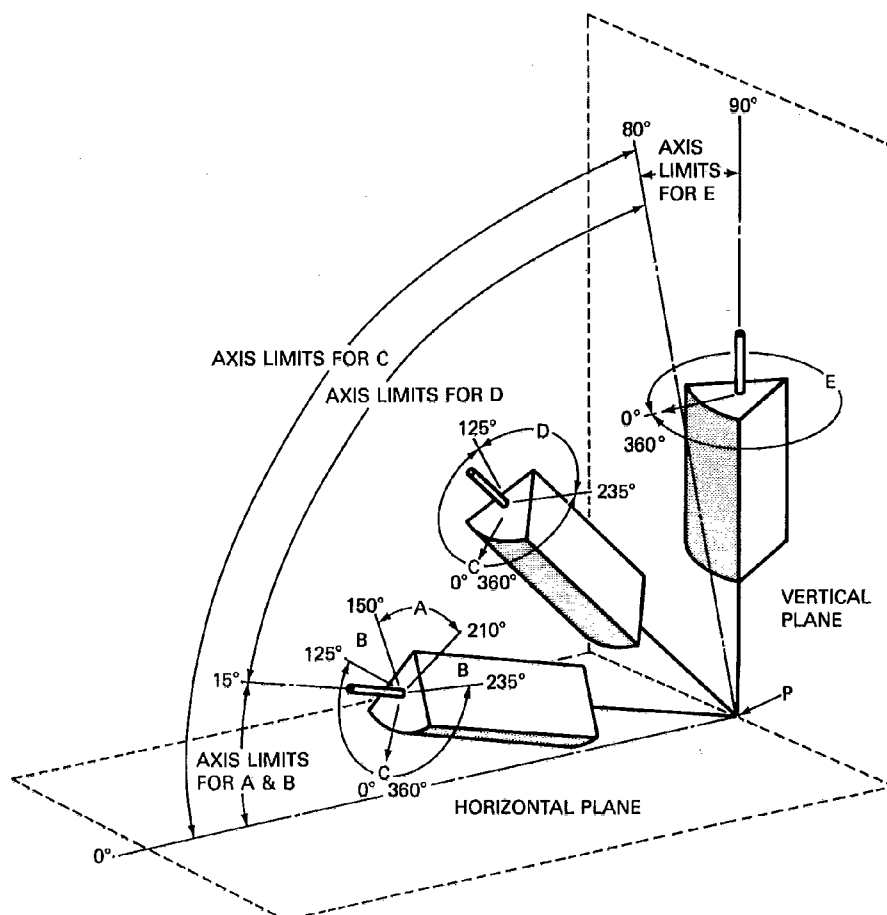
- (1) Fumes and gases
- (2) Radiation (non-ionizing)
- (3) Electric shock
- (4) Noise
- (5) Other factors

10.2 Discussion of Potential Hazards

10.2.1 Metal Fumes are extremely small (sub-micron) particles produced by the vaporization and subsequent recondensation of metals. Health hazards associated with these depend on the toxicity of the specific metal(s) and their concentration and form in the fume.

10.2.1.1 The composition of welding fumes is dependent on the electrode being used, the alloy being welded, welding process utilized, and the coatings on the base metal. The relationship of the welder's head with respect to the fume, and the effectiveness of control measures, such as ventilation and personal protective equipment, are critical factors in influencing the welders exposure.

10.2.1.2 Gas metal arc welding is used to weld all of the steels and many alloy metals with bases of chromium, nickel, aluminum, and copper. The fumes associated with the gas metal-arc welding generally are much less dense than those produced by either shielded metal arc welding or flux cored arc welding because shielding does not depend on the decomposition of a flux coating. Nonetheless, excessive fume concentration can be encountered if adequate ventilation is not provided. The ventilation and protection requirements listed in ANSI/ASC Z49.1 should be followed. These fumes will contain iron oxide when steel is being welded and significant levels of the other metals when alloys are welded.

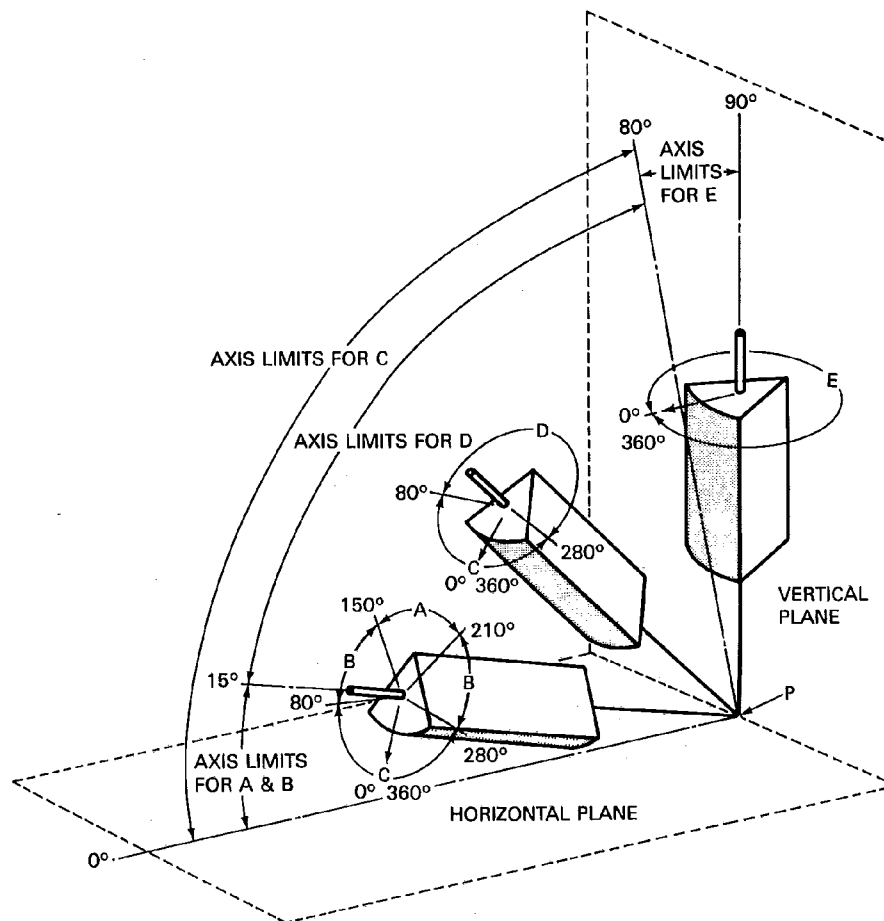


TABULATION OF POSITIONS OF FILLET WELDS			
POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° to 15°	150° to 210°
HORIZONTAL	B	0° to 15°	125° to 150° 210° to 235°
OVERHEAD	C	0° to 80°	0° to 125° 235° to 360°
VERTICAL	D	15° to 80°	125° to 235°
	E	80° to 90°	0° to 360°

NOTES:

1. THE HORIZONTAL REFERENCE PLANE IS ALWAYS TAKEN TO LIE BELOW THE WELD UNDER CONSIDERATION.
2. THE INCLINATION OF AXIS IS MEASURED FROM THE HORIZONTAL REFERENCE PLANE TOWARD THE VERTICAL REFERENCE PLANE.
3. THE ANGLE OF ROTATION OF THE FACE IS DETERMINED BY A LINE PERPENDICULAR TO THE THEORETICAL FACE OF THE WELD WHICH PASSES THROUGH THE AXIS OF THE WELD. THE REFERENCE POSITION (0°) OF ROTATION OF THE FACE INVARIABLY POINTS IN THE DIRECTION OPPOSITE TO THAT IN WHICH THE AXIS ANGLE INCREASES. WHEN LOOKING AT POINT P, THE ANGLE OF ROTATION OF THE FACE OF THE WELD IS MEASURED IN A CLOCKWISE DIRECTION FROM THE REFERENCE POSITION (0°).

Figure 64 – Position of Fillet Welds



TABULATION OF POSITIONS OF GROOVE WELDS

POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° to 15°	150° to 210°
HORIZONTAL	B	0° to 15°	80° to 150° 210° to 280°
OVERHEAD	C	0° to 80°	0° to 80° 280° to 360°
VERTICAL	D	15° to 80°	80° to 280°
	E	80° to 90°	0° to 360°

FOR GROOVE WELDS IN PIPE THE FOLLOWING DEFINITIONS SHALL APPLY:

HORIZONTAL FIXED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE AND THE PIPE IS NOT ROTATED DURING WELDING.

HORIZONTAL ROLLED POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 30° FROM THE HORIZONTAL PLANE, THE PIPE IS ROTATED DURING WELDING, AND THE WELD METAL IS DEPOSITED WITHIN AN ARC NOT TO EXCEED 15° ON EITHER SIDE OF A VERTICAL PLANE PASSING THROUGH THE AXIS OF THE PIPE.

VERTICAL POSITION: WHEN THE AXIS OF THE PIPE DOES NOT DEVIATE BY MORE THAN 10° FROM THE VERTICAL POSITION. (THE PIPE MAY OR MAY NOT BE ROTATED DURING WELDING.)*

*POSITIONS IN WHICH THE AXIS OF THE PIPE DEVIATES BY MORE THAN 10° AND LESS THAN 60° FROM THE VERTICAL SHALL BE CONSIDERED INTERMEDIATE.

Figure 65 – Position of Groove Welds

Most low carbon electrodes are copper coated. The amount of copper fume generated is directly proportional to the overall copper content of the electrode and base metal.

10.2.1.3 The physiological effects of the fumes produced will vary with the metal involved. Exposure must be evaluated on individual fume exposure basis.

10.3. Gases

10.3.1 Ozone

10.3.1.1 Ozone is a gas with a very pungent distinctive odor. It may be injurious to the lungs, upper respiratory system, and eyes.

10.3.1.2 The ultraviolet light emitted by the GMAW arc acts on the oxygen in the surrounding atmosphere to produce ozone, the amount of which will depend upon the intensity and the wave length of the ultraviolet energy, the humidity, the amount of screening afforded by any welding fumes, and other factors. The ozone concentration will generally be increased with an increase in welding current, with the use of argon as the shielding gas, and when welding highly reflective metals. If the ozone cannot be reduced to a safe level by ventilation or process variations, it will be necessary to supply fresh air to the welder either with an air supplied respirator or by other means.

10.3.1.3 Ozone exposures during typical welding operations are generally below accepted guidelines. Certain conditions, such as welding in confined spaces or on highly reflective surfaces using argon-rich gases, may result in exposures exceeding published limits.

10.3.1.4 The lack of a pilot source for ozone generation makes it important to measure exposures in both the welder's and helper's breathing zones. Exposure standards are presented as eight-hour averages, making it difficult to evaluate exposures using grab sample techniques.

10.3.1.5 Since ozone is produced by ultraviolet radiation, generation of ozone away from the arc is possible. This can be aggravated by surfaces reflective to ultraviolet radiation. For this reason, local exhaust ventilation at the arc may not sufficiently control exposures to ozone, use of dilution

ventilation may also be necessary. If welding is performed in confined spaces, the ventilation and personal protection requirements set forth in the latest edition of ANSI/ASC Z49.1 will provide adequate protection, if followed.

10.3.2 Oxides of Nitrogen

10.3.2.1 Oxides of nitrogen may be injurious to the lungs, upper respiratory system, and eyes.

10.3.2.2 Nitrogen dioxide is the end result of a reaction between atmospheric nitrogen and oxygen and the electric arc. The intermediate, nitric oxide converts to nitrogen dioxide at a rate slow enough for both substances to be present. While both substances have similar modes of action, nitrogen dioxide is the more toxic of the two and has a correspondingly lower exposure limit.

10.3.2.3 Certain welding operations may generate significant amounts of oxides of nitrogen. These processes should be evaluated. If problems are detected, the provisions set forth in the latest edition of ANSI/ASC Z49.1 for ventilation will provide adequate protection.

10.3.3 Carbon Monoxide

10.3.3.1 Carbon monoxide (CO) is a colorless, tasteless, and odorless gas. It combines with hemoglobin in red blood cells to form carboxyhemoglobin which interferes with the oxygen carrying capacity of the blood. Thus, chemical asphyxiation may result.

10.3.3.2 Significant carbon monoxide concentrations may be generated from CO₂ gas metal arc welding. Concentrations of CO are higher in the welding plume. Where concentrations are excessive, provide adequate ventilation in accordance with ANSI/ASC Z49.1.

10.3.4 Chlorinated Hydrocarbon

10.3.4.1 Decomposition products of chlorinated hydrocarbon can include toxic gases such as phosgene, hydrogen chloride, and chlorine. These products may be injurious to the lungs, upper respiratory system, eyes, and skin.

10.3.4.2 Experimental evidence has shown that chlorinated hydrocarbon vapors in the vicinity

of an arc (even though not in direct contact with the arc) decompose rapidly. The decomposition is caused by ultraviolet radiation from the arc rather than by the high temperature of the arc. Although the concentration of chlorinated hydrocarbon vapors may be too low to be detectable by the sense of smell, welding in areas containing chlorinated hydrocarbon vapors can produce excessive concentrations of noxious gases including phosgene. Far greater decomposition is produced by argon than by helium because of the greater radiation intensity when using argon.

10.3.4.3 Typical sources of chlorinated hydrocarbons are cleaning/wiping operations, degreasers, and paint stripping. Degreasers and other sources of these vapors should be located so that no vapor will be exposed to radiation from the arc.

10.3.5 Oxygen Deficiency

10.3.5.1 Shielding gases can displace oxygen in enclosed and confined spaces. This can result in simple asphyxiation without warning.

10.3.5.2 Argon, helium, carbon dioxide and nitrogen are commonly used shielding gases in electric welding process. These inert, colorless, odorless and tasteless gases cannot be detected by the human senses at concentrations normally present in welding operations. An atmosphere with less than eighteen percent oxygen can cause dizziness; breathing less oxygen may result in unconsciousness, or even death.

10.3.5.3 Tanks and confined spaces should be checked for oxygen content prior to entry. The ventilation requirements set forth in the latest edition of ANSI/ASC Z49.1 should be followed.

10.4 Radiation (Non-ionizing)

10.4.1 Radiant energy, particularly in the ultraviolet short range, is much more intense during gas metal arc welding than during shielded metal arc welding. It may injure bare skin and the unprotected eyes. Greater intensities of ultraviolet radiation cause rapid disintegration of cotton clothing.

10.4.2 The total radiant energy produced by the gas metal arc is approximately twice as great as that produced by the shielded metal arc at equal current values. The shielding gas employed can have signif-

icant effects on the amount of radiant energy emitted from the arc.

Since visible light is also increased with gas metal arc welding, it is recommended that welders use the darkest shade of filter shade that permits adequate visibility of the welding operation.

Adequate eye protection is provided by the filter shade recommended in ANSI/ASC Z49.1.

Leather, wool and aluminum-coated cloth are reported to withstand the action of radiation energy reasonably well. However, aluminum coated cloth may present reflection and conductivity hazards.

10.5 Electric Shock

10.5.1 Open Circuit Voltage. Electric shock can result from open-circuit voltage. Open-circuit voltages can be additive and increase the severity of the shock hazard when multiple machines are used.

10.5.2 Ground of Equipment and Workpiece. All electrical equipment and the workpiece must be connected to an approved electrical ground to prevent electrical shock.

10.5.3 Moisture. The area, equipment, and clothing must be kept as dry as practical to prevent electrical shock.

10.5.4 Cable Size and Connections. Underrated cable or poor electrical connections, or both, may cause failure, and thus, represent both a shock and fire hazard. Welding cables must be of a size adequate for current and duty cycles to be reasonably expected.

10.6 Noise. Exposure to excessive noise levels for extended periods of time may result in hearing impairment. Associated activities may produce excessive noise levels. Exposed workers should wear properly fitted ear protection.

10.7 Other Factors

10.7.1 Cylinder Rupture

10.7.1.1 Never strike an arc on a cylinder, and insure that cylinders are electrically insulated from the work circuit. The defect produced by an arc-burn on a compressed gas cylinder weakens the cylinder. If ruptured, high pressure cylinders can be turned into potentially lethal projectiles.

10.7.1.2 Gas cylinders shall be secured to prevent them from falling. Do not move cylinders with regulators attached.

10.7.2 Fire Hazard

10.7.2.1 Hot slag, sparks, and arc radiation act as a source of ignition, and burns.

10.7.2.2 Workers shall be familiar with fire-prevention and fire and burn protection measures.

10.7.3 Heat Stress

10.7.3.1 Acclimatization to heat involves both physiological and psychological adjustments during

the first week of exposure. Caution must be employed when unacclimated or physically unfit workers are exposed to heat stress operations.

10.7.3.2 Physiological responses to hot environments include heat rash, heat cramps, heat exhaustion, and heat stroke.

10.7.4 Wire Feed Mechanisms

10.7.4.1 When working close to drive rolls, be cautious of moving parts.

10.7.4.2 Guard against accidental activating of wire feed mechanism because of personal injury.