TENTH EDITION

WELDING HANDBOOK

VOLUME 1

Welding and Cutting Science and Technology

Welding Handbook

Tenth Edition

Volume 1

WELDING AND CUTTING SCIENCE AND TECHNOLOGY

Prepared under the direction of the
Welding Handbook Committee

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Welding Handbook, Tenth Edition

Volume 1 *Welding and Cutting Science and Technology*

Projected:

Volume 2 *Welding Processes—Arc Welding and Cutting*

Volume 3 *Welding Processes—Resistance, Solid-State, Oxyfuel, Brazing, and Soldering*

Volume 4 *Materials and Applications—Ferrous and Surfacing Metals, and Maintenance and Underwater Applications*

Volume 5 *Materials and Applications—Nonferrous and High-Temperature Metals, and Nonmetallic Materials*

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Tenth Edition

Volume 1

WELDING AND CUTTING SCIENCE AND TECHNOLOGY

American Welding Society

First Printing: November, 2018

Library of Congress Control Number: 2018953522
Print—ISBN: 978-1-64322-014-7
PDF—ISBN: 978-1-64322-015-4

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DEDICATION

Harvey R. Castner

In recognition of his distinguished service
to the welding industry and his
enduring contributions to the Welding Handbook

Harvey R. Castner—welding engineer, manager, researcher, mentor, and welding industry expert—used his extensive technical expertise to expand the technology of welding for today and future generations. He generously shared the knowledge acquired during his career in the welding industry by serving on various industry committees, including the *Welding Handbook* Committee. He joined AWS in 1962 and has been active throughout his working career.

Harvey served as a *Welding Handbook* chapter volunteer beginning in the early 1990s and became a Committee member in 1993. He has provided valuable guidance to the Committee on the organization and technical content, serving as the *Welding Handbook* Committee Chair from 1999 to 2004. He continued providing support after his term as Chair through oversight and final reviews of various chapters in subsequent volumes of the 9th edition.

He holds a B.S. degree in Welding Engineering from The Ohio State University and an M.B.A. from Kent State University. He began his career at Allis Chalmers Corporation in Milwaukee Wisconsin and moved on to the Edison Welding Institute in Columbus, Ohio. He served not only as a welding engineer, but also as a project manager and senior technical manager, leading various research projects. He is a Fellow of the American Welding Society, an AWS Life Member, and recipient of the James F. Lincoln Gold Medal Award. He is also a past member of the AWS Board of Directors. Harvey has tirelessly worked for the improvement of the greater welding community through his technical research, and development of the next generation of welding personnel.

The *Welding Handbook* Committee is honored to dedicate this Volume to Harvey R. Castner for his loyal devotion and service to AWS and the *Welding Handbook*.

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PART IV—QUALITY, TESTING STANDARDS, AND METHODS

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ACKNOWLEDGMENTS

The Welding Handbook Committee of the American Welding Society and the editor gratefully recognize the contributions of the volunteers who have created, developed, and documented the technology of welding and shared it in past editions of the *Welding Handbook*, beginning with the first edition published in 1938. The enthusiasm and meticulous dedication of the authors and technologists reflected in the previous nine editions of the *Welding Handbook* are continued in this volume of the tenth edition.

This volume was compiled by the members the Welding Handbook Volume 1 Committee and the WH1 Chapter Committees, with oversight by the Welding Handbook Committee. Chapter committee chairs, chapter committee members, and oversight persons are recognized on the title pages of the chapters.

The Welding Handbook Committee and the editor recognize and appreciate the AWS technical committees who developed the consensus standards that pertain to this volume, and acknowledge the work of the editors of all previous editions. The Welding Handbook Committee is grateful to members of the AWS Technical Activities Committee and the AWS Safety and Health Committee for their reviews of the chapters. The editor appreciates the AWS Publications staff and Standards Development staff for their assistance during the preparation of this volume.

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PREFACE

This volume of the *Welding Handbook* presents an overview of the most recent research and engineering developments in the field of welding and cutting science and technology. Upcoming volumes will address welding processes, materials, and applications. Together, the five volumes of the tenth edition substantially expand upon and update the information presented in the ninth edition.

The seventeen chapters in this volume cover the fundamentals of welding, cutting, joining, and allied processes. The chapters discuss metallurgy, the physics of welding and cutting, heat flow in welding, and residual stress and distortion. Other important topics include engineering considerations of weld design, weldment tooling and positioning, automation, process monitoring and control, methods for the evaluation and testing of welds, weld quality, weld inspection and nondestructive examination, and the economics of welding.

Well-researched chapters on codes and other standards, the qualification and certification of welding techniques and personnel, the accurate communication of welding information, and safe practices are also included. The information in this volume is applicable to all categories of welding, from manual welding to the most sophisticated automated and robotic systems.

The peer-reviewed chapters in this volume are enhanced by the pertinent consensus standards that are referenced throughout. More than 700 drawings, schematics, and photographs illustrate the text. Approximately 170 tables provide categorized or comparative information. Explanatory information and sources are identified and referenced in footnotes.

This volume, like the others preceding it, is a voluntary effort by the members of the Welding Handbook Committee, the Welding Handbook Volume 1 Committee, and the Chapter Committees. Each chapter is reviewed by members of the American Welding Society's Technical Activities Committee (TAC), Safety and Health Committee (SHC), and other specialists.

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CHAPTER 1

SURVEY OF JOINING, CUTTING, AND ALLIED PROCESSES

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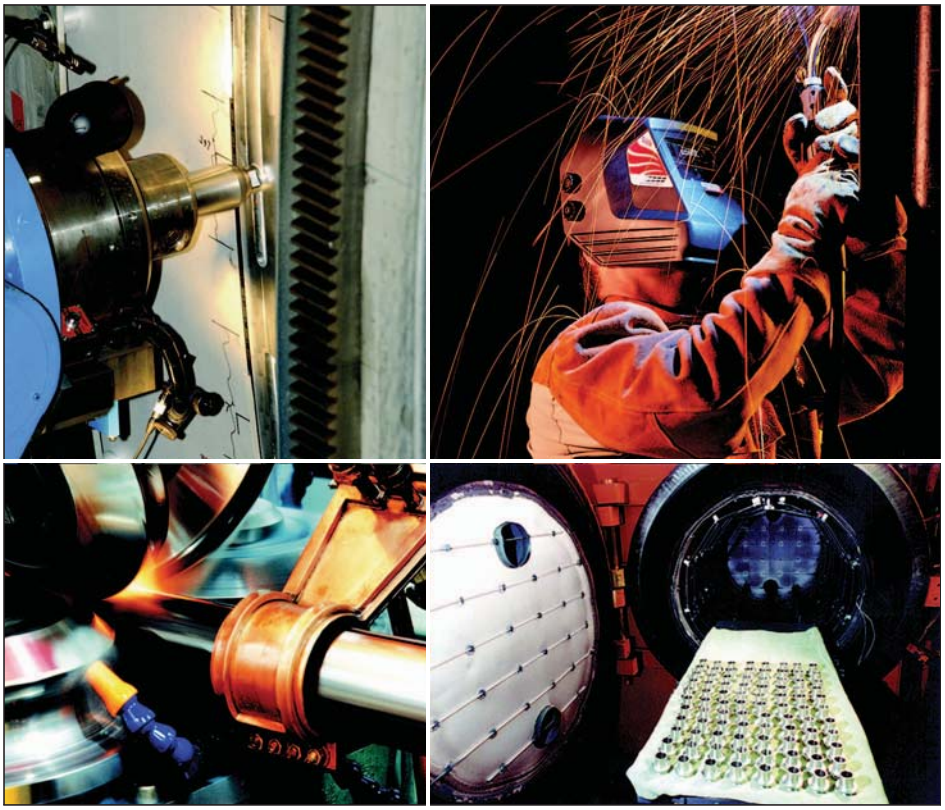

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CHAPTER 1

SURVEY OF JOINING, CUTTING, AND ALLIED PROCESSES

INTRODUCTION

This chapter introduces the basic concepts of the conventional and more widely used joining, cutting, and thermal spraying processes. The distinguishing features of the various processes are summarized and compared to one another. Among the joining processes reviewed are the electric arc, resistance, and solid-state welding processes as well as brazing, soldering, and adhesive bonding. The cutting processes examined include thermal and nonthermal methods of material removal. Thermal spray processes, including flame spraying (FLSP), plasma arc spraying, arc spraying, and detonation flame spraying, will also be reviewed in this chapter.[1, 2, 3]

Several processes may be applicable for a specific job; the challenges include selecting the process that is most suitable for the specific application, code requirements, schedule, and cost. However, these factors may not be compatible with each other and may require a compromise. The selection of the optimum process ultimately depends on several criteria, including the number of components to be fabricated, capital equipment costs, joint location, structural mass, and the preferred performance of the product. The adaptability of the process to the location of the operation, the type of manufacturing environment, and the experience and skill levels of the employees may also have an impact on the final selection. In this chapter, these criteria are examined as they relate to the various joining, cutting, and thermal spraying processes.

This chapter is intended to serve as a survey of the most common joining, cutting, and thermal spraying processes; therefore the reader is encouraged to conduct a thorough investigation of the processes that appear to have the best potential for the intended applications. This investigation should consider safety and health recommendations such as those presented in the American National Standard *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1,[4] and the information provided in the manufacturers' safety data sheet (SDS). Additional sources of information about the joining, cutting, and allied processes are listed in the Bibliography and Supplementary Reading List at the end of this chapter. In particular, *Welding Processes*,[5] Volume 2 and Volume 3 of the American Welding Society's *Welding Handbook*, presents in-depth coverage of each of the processes.

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[1] Welding terms and definitions used throughout this chapter are from American Welding Society (AWS) Committee on Definitions and Symbols, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, AWS A3.0M/A3.0, Miami: American Welding Society.

[2] At the time this chapter was prepared, the referenced codes and other standards were valid. If a code or other standard is cited without a date of publication, it is understood that the latest edition of the referenced document applies. If a code or other standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code are not included; however, as codes and standards undergo frequent revision, the reader should consult the most recent edition.

[3] The AWS *Welding Handbook* makes use of both U.S. Customary Units and the International System of Units (SI). The latter are shown within parentheses ( ) in the text and in appropriate columns in tables and figures. SI measurements may not be exact equivalents; therefore, each system must be used independently.

[4] American National Standards Institute (ANSI), *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1, Miami: American Welding Society.

[5] American Welding Society (AWS) Welding Handbook Committee, 2004, *Welding Processes*, Part 1, Vol. 2 and 2007, *Welding Processes, Part 2*, Vol. 3 of *Welding Handbook*, 9th ed., Miami: American Welding Society.

JOINING PROCESSES

The goal of all joining processes is to combine individual pieces of material into a single component. In the case of two pieces of compatible metal, if the atoms at the contacting surface of one piece come close enough to the atoms at the contacting surface of the other piece, then interatomic pull will develop and the two pieces will become one. Although this concept is easy to describe, it does not usually happen under typical conditions.

Surface roughness, impurities, fitting imperfections, and the varied properties of the materials make it nearly impossible for this ideal scenario to occur so thermal (heat) and mechanical energy (pressure) is required to eliminate these barriers and thereby make joining possible. Welding processes and procedures have been developed to provide the thermal, mechanical or a combination of both energies required to overcome these difficulties and to activate the adjoining surfaces.

Most welding processes apply significant thermal energy to the base material which can reach temperatures that can be ten times the melting temperature of the base metal, causing melting and vaporization. The temperatures that are reached in many of the welding processes typically cause changes in the base metal microstructure and composition which can be detrimental to the properties of the materials being joined. Hot metals tend to oxidize rapidly at elevated temperatures so sufficient protection must be provided to prevent this detrimental reaction. Some metals are more sensitive than others, in which case protection from oxidation can become more demanding. The method by which sufficient protection against oxidation is provided by the process should then be identified. When determining which welding process to use, one must consider what effect the heat input from each of the welding processes being evaluated will have on the base metal, weld passes, as well as how any of the resulting microstructural changes will impact the function of the components being joined.

The selection of an appropriate joining and cutting process for a given task involves a number of considerations. These include the following:

1. Availability of the welding process;
2. Suitability of the welding process for the environment in which welding is to be done;
3. Skill requirements;
4. Weldability of the base metals with respect to type and thickness to be joined;
5. Availability of suitable welding consumables;
6. Weld joint design;
7. Heat input requirements;
8. Demands of the welding position;
9. Cost of the process, including capital expenditures, materials, and labor;
10. Number of components to be fabricated;
11. Delivery requirements;
12. Applicable code and/or standard requirements; and
13. Safety concerns.

The overview of the joining processes featured in Table 1.1 presents an initial reference guide to the capabilities of various joining processes with respect to a variety of ferrous and nonferrous metals. This table indicates the processes, materials, and material thickness combinations that are typically compatible. The columns on the left list various engineering materials and four arbitrary thickness ranges. The processes most commonly used in industry are listed across the top.

It should be noted that additional information, such as the considerations listed above, must be taken into account before process selections are finalized. Table 1.1 can be a useful tool in providing general guidelines for the screening and selection process. In addition, six-sigma methodologies, such as Failure Effect Mode Analysis, or FMEA, can also be useful to minimize the potential causes of failure during the evaluation process.

ARC WELDING

The term *arc welding* applies to a large, diversified group of welding processes that use an electric arc as the source of heat. The creation of a weld between metals using these processes does not usually involve pressure. The process may or may not utilize a filler metal. The arc is initiated between the workpiece and the tip of the electrode. The intense heat produced by the arc melts the base metal in the area of the arc which upon cooling results in the formation of a weld. The electric arc may be either moved along the joint to produce the weld or held stationary while the workpiece is moved under the process.

Arc welding can be performed by conducting the welding current through consumable electrodes such as a wire or rod, or it can be done using nonconsumable electrodes of carbon or tungsten rods. Metal arc processes utilize consumable electrodes that melt the electrode filler metal along with the base metal to create the weld. Some arc welding processes may also produce a slag covering to protect the molten metal from oxidation or support out-of-position welding.

The nonconsumable arc processes generate a weld by melting the base metal only, resulting in what is termed an *autogenous weld*. The nonconsumable electrode serves only to sustain the arc. If filler metal is required in a nonconsumable process, it may be fed either manually or mechanically into the molten weld pool.

Table 1.1
Capabilities of the Commonly Used Joining Processes

		Processes																						
Material	**Thickness**	**SMAW**	**SAW**	**GMAW**	**FCAW**	**GTAW**	**PAW**	**ESW**	**EGW**	**RW**	**FW**	**OFW**	**DFW**	**FRW**	**EBW**	**LBW**	**TB**	**FB**	**RB**	**IB**	**DB**	**IRB**	**DFB**	**S**
Carbon steel	S	x[*]	x	x		x				x	x	x			x	x	x	x	x	x	x	x	x	x
	I	x	x	x	x	x				x	x	x		x	x	x	x	x	x	x	x	x	x	x
	M	x	x	x	x					x	x	x		x	x	x	x	x	x				x	
	T	x	x	x	x			x	x		x	x		x	x			x					x	
Low-alloy steel	S	x	x	x		x				x	x	x	x		x	x	x	x	x	x	x	x	x	x
	I	x	x	x	x	x				x	x		x	x	x	x	x	x	x				x	x
	M	x	x	x	x					x	x		x	x	x	x	x	x	x				x	
	T	x	x	x	x			x			x		x	x	x		x					x		
Stainless steel	S	x	x	x		x	x			x	x	x	x		x	x	x	x	x	x	x	x	x	x
	I	x	x	x	x	x	x			x	x		x	x	x	x	x	x	x				x	x
	M	x	x	x	x		x				x		x	x	x	x	x	x	x				x	
	T	x	x	x	x			x			x		x	x	x			x					x	
Cast iron	I	x										x					x	x	x				x	x
	M	x	x	x	x							x					x	x	x				x	x
	T	x	x	x	x							x						x					x	
Nickel and alloys	S	x		x		x	x			x	x	x			x	x	x	x	x	x	x	x	x	x
	I	x	x	x		x	x			x	x			x	x	x	x	x	x				x	x
	M	x	x	x			x				x			x	x	x	x	x					x	
	T	x		x				x			x			x	x			x					x	
Aluminum and alloys	S	x	x	x		x	x			x	x			x	x	x	x	x		x	x		x	x
	I	x		x		x	x				x			x	x	x		x		x	x			
	M	x		x			x				x			x	x	x		x		x				
	T			x							x			x	x									
Titanium and alloys	S			x		x	x			x	x		x		x	x		x	x			x	x	
	I			x		x	x				x		x	x		x		x					x	
	M			x		x	x				x		x	x		x		x					x	
	T			x			x				x		x		x	x		x					x	
Copper and alloys	S			x		x	x			x[†]	x				x		x	x	x	x			x	x
	I			x						x				x				x		x			x	x
	M			x						x				x				x					x	
	T			x										x				x					x	
Magnesium and alloys	S			x		x				x					x	x	x	x			x		x	
	I			x		x				x				x	x	x	x	x			x		x	
	M			x										x	x	x		x					x	
	T			x											x									
Refractory alloys	S			x		x	x			x	x				x		x	x	x	x		x	x	
	I			x			x			x	x				x		x	x					x	
	M										x													
	T																							

LEGEND

Process Code:

SMAW = shielded metal arc welding
SAW = submerged arc welding
GMAW = gas metal arc welding
FCAW = flux cored arc welding
GTAW = gas tungsten arc welding

PAW = plasma arc welding
ESW = electroslag welding
EGW = electrogas welding
RW = resistance welding
FW = flash welding

OFW = oxyfuel gas welding
DFW = diffusion welding
FRW = friction welding
EBW = electron beam welding
LBW = laser beam welding

TB = torch brazing
FB = furnace brazing
RB = resistance brazing
IB = induction brazing

DB = dip brazing
IRB = infrared brazing
DB = diffusion brazing
S = soldering

Thickness:

S = sheet: up to 3 mm (1/8 in.)
I = intermediate: 3 to 6 mm (1/8 to 1/4 in.)
M = medium: 6 to 19 mm (1/4 to 3/4 in.)
T = thick: 19 mm (3/4 in. and up).

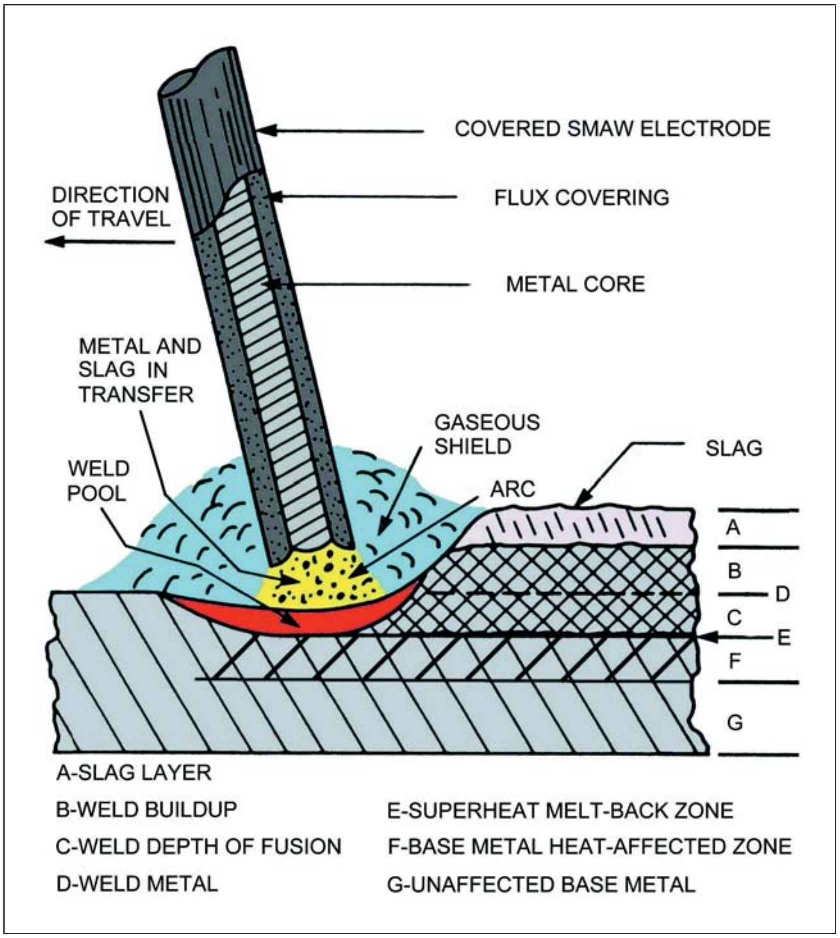
[*] Commercial process.

[†] Copper requires molybdenum-coated tips.

Shielded Metal Arc Welding

Illustrated in Figure 1.1, shielded metal arc welding (SMAW) is used to weld ferrous and some nonferrous metals. SMAW is sometimes referred to colloquially as *stick welding* or simply *arc welding*. This process incorporates the use of a metal arc (an arc that transfers metal) which is formed between a covered electrode and the weld pool. The electrode typically consists of a solid wire core around which a concentric flux mixture of silicate binders and powdered materials such as fluorides, carbonates, oxides, metal alloying elements, and cellulose is extruded. This covering serves as a source of arc stabilizers and vapors to displace air as well as metal and slag to protect, support, and insulate the hot weld metal.[6]

The process name *shielded metal arc* could be used to describe a number of arc processes because most use some means of shielding to protect the molten weld pool. However, this term is unique to the process in which shielding is achieved by means of the decomposition of the coating on the electrode as it is consumed by the heat of the arc.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.8.

Figure 1.1—Schematic Representation of Shielded Metal Arc Welding

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[6] An excellent guide to the classification of SMAW electrodes is provided in the appendices of the applicable filler metal specifications. See, for example, American Welding Society (AWS) Committee on Filler Metals, *Specification for Covered Carbon Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.1/A5.1M, Miami: American Welding Society.

The bare section of the electrode is clamped into an electrode holder, which is connected to the power source by a cable. The workpiece is connected to the other power source terminal. The arc is initiated by touching the tip of the electrode on the workpiece and then withdrawing it slightly, thus initiating the arc. The heat of the arc melts the base metal in the immediate area of the arc initiation along with the electrode's metal core and covering. The molten base metal, the wire core, and any metal powders in the covering coalesce to form the weld.

When arc welding was developed during the latter part of the nineteenth century, welding was more difficult due to the less-than-ideal electrical power sources available and the fact that a bare metal rod was used as the consumable electrode. This bare metal electrode made it very difficult to initiate and maintain an arc. Also, the bare electrode provided no protection from the atmosphere and the resulting weld had poor properties.

Flux coatings for welding electrodes were developed in the 1920s and have undergone improvements in terms of formulation and production since that time. These improvements have resulted in ease of arc initiation and operation as well as excellent weld properties. The ingredients in the coatings stabilize the arc by providing continual ionization of the arc column and they produce (1) shielding vapors, which displace air; (2) deoxidizers and other scavengers that purify the weld; (3) additional alloying elements; and (4) slag, which provides a physical protection or covering over the hot weld metal. Electrode coatings that incorporate powdered metal can increase the deposition rate and enable the operator to drag the electrode lightly on the coating instead of having to maintain a proper arc length manually. This tends to reduce operator fatigue, minimizes skill requirements, and often increases productivity.

Covered welding electrodes are available in diameters ranging from 1/16 inch (in.) to 5/16 in. (1.6 millimeters [mm] to 7.9 mm). The smaller diameters are used with low currents for the joining of thin sections, limited-access work, and welding in the vertical and overhead welding positions. The larger-diameter electrodes require higher currents, which produce higher weld deposition rates. With respect to economy, the goal is to use the electrode with the highest deposition rate and the highest current practical for the application.

In order to realize the economic potential of the larger electrodes, the amperage per square inch (in.^{2}) (square millimeter [mm^2]) of the electrode cross-sectional area, termed *current density*, must be optimized. Although electrodes can function at a significantly lower current density than the optimum setting, a low current density decreases productivity. Weld deposition rates vary directly in relation to the current density used. Smaller electrodes cannot conduct currents as high as larger diameter electrodes, but they are able to maintain a high current density. In many cases, small electrodes with higher current densities can yield higher deposition rates and deeper penetration than larger electrodes with lower current densities.

The application of the SMAW process involves relatively high labor costs due to lower process efficiency and the higher skilled labor required. This process yields a deposition efficiency of less than 60% based on a comparison of the weight of electrodes purchased to the weld weight obtained. This relatively low efficiency is due to several factors. These include the discarding of electrode stubs when the electrode is consumed to within 2 in. to 3 in. (50.8 mm to 76.2 mm) of the electrode holder or when a portion of the covering is knocked off. In addition, slag must be chipped from the completed weld. Compared to the wire-feed arc processes, the labor costs of the shielded metal arc process are high due to its slower deposition rates, higher degree of skill required, time loss associated with changing electrodes, and the removal of the slag from the weld after each pass.

The equipment used in SMAW is the simplest and least expensive of that used for the electric welding processes. The necessary components are a power source of adequate current rating and duty cycle, suitably sized electrical cables, an electrode holder, and a workpiece-lead clamp. Utility-duty, single-phase alternating-current (AC) welding machines are the least expensive and can be used with small electrodes designed for AC current. Industrial-duty alternating current/direct current (AC/DC) or DC power sources can be used with the greatest variety of electrodes. Engine-driven portable machines with a wide range of capabilities are marketed at various prices, depending on the polarity and power output options desired.

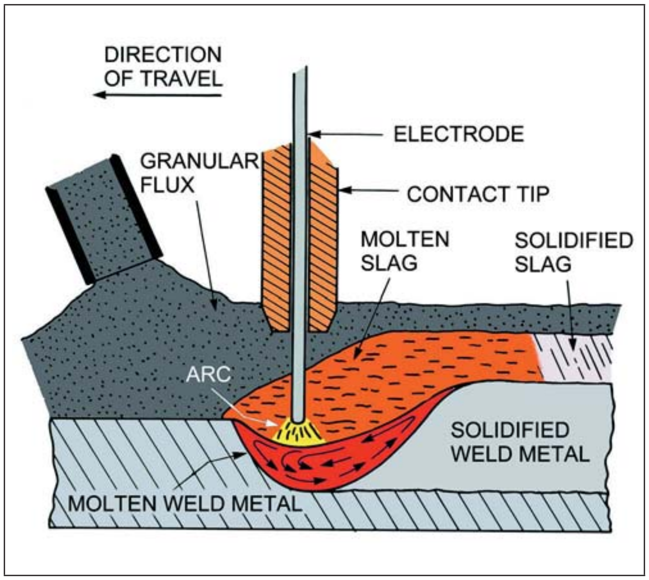
With respect to personal protective equipment, SMAW operators must wear sturdy dry clothing and leather gloves for protection against spatter and electric shock. A helmet should be equipped with a dark lens (shade number 10 or higher recommended for most applications) that shields the eyes from the brilliance of the arc, electromagnetic radiation, and flying slag particles or weld spatter.

The SMAW process offers several advantages in addition to the simplicity, low cost, and portability of SMAW equipment. With this process, shops can handle many welding applications using a wide variety of electrodes. Moreover, this process permits welds to be made in confined spaces. For these reasons, SMAW is used in the construction, pipeline, and maintenance industries, among others.

Disadvantages include low deposition rates, the inability to automate, and a higher level of skill to perform it. The need for frequent starts and stops creates conditions for cold laps, crater cracks, and similar problems if performed improperly.

Submerged Arc Welding

A versatile production welding process with high productivity, submerged arc welding (SAW) joins metals by heating them by an electric arc formed between a continuously fed, bare metal electrode that can be either a solid wire or cored wire and the workpiece. Illustrated in Figure 1.2, this process involves establishing and maintaining the welding arc submerged beneath a mound of granular flux particles. Additional flux is continually added in front of the electrode as welding progresses. The flux helps in stabilizing the arc, protecting the molten weld metal from contamination from the ambient atmosphere and may influence the chemical properties of the weld if an active flux is used. The arc quickly melts a portion of the flux and base metal but remains covered by a combination of melted and unmelted flux. Therefore, the arc generally cannot be seen because it is submerged under the flux and molten slag covering. When welding is completed, any unmelted flux is typically removed and can be reused after screening out any slag particles from it. Because some of the flux particles are damaged during recycling, typically reused flux is mixed in an even 50-50 mix ratio with fresh flux. The melted flux forms a slag covering which must be removed after welding is complete or before any additional weld passes can be made.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.18.

Figure 1.2—Schematic of Submerged Arc Welding

Used extensively in pipe manufacturing, pressure vessel fabrication, bridge fabrication and ship-building, submerged arc welding is most widely employed in the welding of many grades of carbon and high strength low-alloy steels. Stainless steel and various nickel alloys are also effectively welded or used as surfacing filler metals with this process. Submerged arc welding is generally automated or robotic, though some industries still use manual or semi-automated application for short welds.

The welding positions best suited for submerged arc welding are the flat position for fillet (1F) and groove (1G) welds and the horizontal (2F) position for fillet welds. The welding of butt joints in the horizontal position (2G) can be accomplished but special flux shelves must be used to support the flux in the horizontal position for welding. Though rarely used, vertical welding has been done using a weaving technique with small diameter wires and specialized equipment. The overhead welding position cannot be utilized in submerged arc welding because the flux covering of the arc and molten pool cannot be maintained due to the effects of gravity.

The wire electrodes used in submerged arc welding are usually supplied in coils or drums. The electrodes can be either solid or tubular, composite wires. Some solid wires may be coated with a thin layer of Cu to improve the wire's corrosion resistance prior to welding and the current conduction during welding. For larger jobs, the larger-sized packages maximize economy by increasing operating efficiency and decreasing electrode unit costs. The electrode wire diameters usually specified in submerged arc welding range between 1/16 in. and 1/4 in. (1.6 mm and 6.4 mm). Due to the high current and deep penetration often used, this process is better suited to welding sections thicker than 1/4 in. (6.4 mm). However, reduced current and 3/64 in. (1.1 mm) or smaller electrode wire can be used for welding thicknesses below 1/4 in. (6.4 mm).

The flux used in submerged arc welding can be selected in combination with the electrode filler metal to yield specific weld properties. Various filler metal-flux combinations produce beneficial chemical reactions and modify the chemical composition of the weld metal. The unmelted flux can be vacuumed from the completed weld and reused once any lumps of slag have been removed through sifting. The reused flux is typically mixed in equal proportions to new flux because the flux particles can become mechanically damaged during the recycling process which can produce too many particle fines. Magnets are often used during sifting to remove any unwanted mill scale or other metallic particles. The melted flux leaves a slag deposit that is easily removed, leaving a bright, clean, smooth weld with no spatter.

However, flux in the area of the weld joint tends to slow the cooling rate of the weld and the adjacent base metal after welding. This effect may impact the hardness profile of the heat-affected zone (HAZ) depending on the chemistry of the base metal and the actual rate of cooling in the HAZ. This may not be acceptable for metal alloys that require high toughness values or for materials that require a faster cooling rate to minimize the HAZ degradation of a tempering treatment. Adjustments to the procedure, such as decreasing the amperage and voltage or increasing the travel speed can help to decrease the heat input and its impact on the HAZ. The common formula for determine heat input for non-waveform power supplies is shown below.

Heat Input (Joules) =

$$\frac{\text{Arc Voltage} \times \text{Welding Current}}{\text{Travel Speed}} \times 60$$

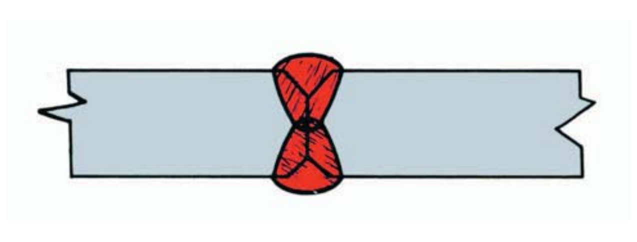
High current densities are possible with submerged arc welding because the flux has a stabilizing effect on the arc. High current densities yield high deposition rates and deep penetration. The deep penetration can minimize the amount of joint preparation required, though the depth-to-width ratio of the weld may be critical in some alloys to prevent centerline cracking in the weld. The high deposition rate and deep penetration result in a high level of productivity. Figure 1.3 illustrates this type of joint.

With submerged arc welding, electrical parameters and the travel speed along the joint can be adjusted to produce a variety of weld profiles, ranging from a wide, flat deposit with little penetration to a deep, narrow weld with a high bead reinforcement or buildup. Alternating current, direct current electrode positive (DCEP) and direct current electrode negative (DCEN) can be used to change to resulting profile of the weld.

Though single-electrode welding is the most common configuration used in submerged arc welding, a combination of multiple electrodes and cold wires (wires not heated by another source) can be used to achieve a higher productivity and penetration control. When two wires with separate power sources are used in SAW, it is referred to as a tandem arc process. A typical SAW tandem arc procedure utilizes DCEP for the first electrode and ac for the second electrode. Deep penetration into the joint root face is achieved by using DCEP on the first electrode, while higher deposition rates and minimal arc blow (deflection of the arc from its axial path due to the effects of magnetic fields) are achieved using AC on the second electrode because it disrupts the continuous flow of the DC magnetic flux fields due to the constant polarity changes. The tandem arc process is typically used to join thicker base metals. As many as five electrodes feeding into the same weld pool can be used. Submerged arc welding can also be performed with a metal strip-type electrode for surfacing applications. This results in a wide deposit with minimal penetration and a high deposition rate.

With no visible arc and very little smoke or fume generation, submerged arc welding offers advantages with respect to environmental safety concerns. Operators need not wear a helmet or heavy protective clothing, though eye protection must be worn to shield against unexpected hazards. Hand protection should be used for handling hot slag and the weldment. Special care should be taken when pouring or otherwise handling flux to avoid breathing the dust that is generated. Because certain elements can be hazardous when vaporized, the manufacturer's safety data sheets (SDSs) should be consulted to identify potentially hazardous materials.

In summary, the main advantages of submerged arc welding are high deposition rates, alloy combinations available, and weld process stability. The main disadvantages are that the process is typically limited in the positions for which it can be used, the flux must be properly stored and maintained, the flux must be reprocessed for reuse, the process cannot typically be used on thin materials and there is a slag waste component which must be addressed.



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.44.

Figure 1.3—Joint with Thick Root Face

Gas Tungsten Arc Welding

The gas tungsten arc welding (GTAW) process, sometimes referred to colloquially as *TIG welding*, incorporates the use of a nonconsumable tungsten electrode to initiate and sustain the arc, which is shielded from the atmosphere by externally supplied gas. The gas is almost always inert, but there are cases were an active gas can be used for very specialized applications. Gas tungsten arc welding is the one of most versatile of the arc welding processes. Welds can be made with or without filler metal and the process can be used to weld very thin materials that are just a few thousandths of an inch (less than 1 millimeter) thick. Gas tungsten arc welding can be used in all welding positions to join just about all weldable ferrous and nonferrous alloys. Internationally, the gas tungsten arc process may also be referred to as TIG–tungsten inert gas or WIG–Wolfram (the chemical element name of tungsten) inert gas. The process may also be called TAG if the shielding gas contains an active component such as an addition of nitrogen or hydrogen.

Gas tungsten arc welding can be used in automated or robotic applications, but is most often used in manual applications. Weld control is excellent in gas tungsten arc welding because voltage can be controlled by the length of the arc, current can be adjusted via welder or automated controls, wire feed is independent of the other variables and travel speed can be varied as required. This excellent control yields exceptional fusion and wetting at the beginning of the weld, thus avoiding incomplete fusion, which can take place when using consumable electrode processes. Figure 1.4 illustrates the gas tungsten arc process.

The shielding gas utilized in gas tungsten arc welding is almost always completely inert. Argon is the predominant shielding gas used, though helium and argon-helium mixtures are sometimes utilized to increase weld penetration. Inert gas shielding displaces the ambient atmosphere so that welding can take place in a nonreactive atmosphere. Reactive gases such as hydrogen or nitrogen are sometimes mixed with the inert gas to obtain specialized effects (example: oxides on 300 series stainless steels are reduced on due to the effects of hydrogen) or to increase productivity. The use of active gases is very limited in industry and used only for very special applications. Because the tungsten electrode may react unfavorably with certain shielding gases, the overall number of shielding gases that can be used with this process is limited.

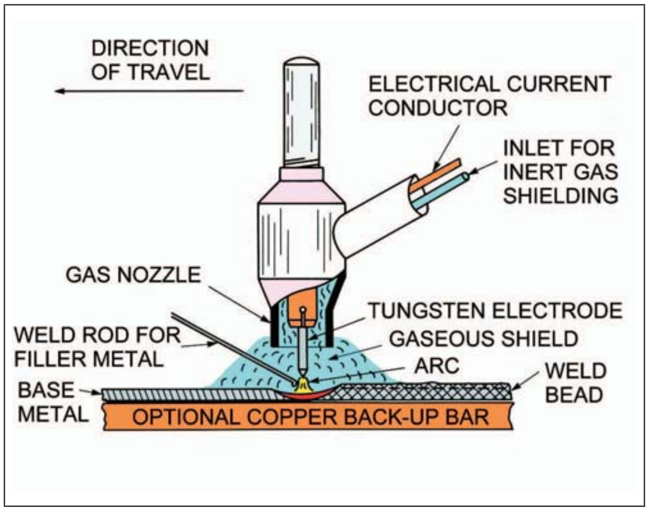


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding

Tungsten electrodes are often alloyed with small amounts of oxides of lanthanum, thorium, or cerium. These oxide additions enhance the electron emission of the electrode and can also raise the melting temperature of the electrode which enables the electrode to be used at a higher current level without inducing melting. The American Welding Society (AWS) standard *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*, AWS A5.12/A5.12M,[7] contains specifications for the tungsten electrodes used in gas tungsten arc welding.

The selection of a power source for gas tungsten arc welding is based on the polarity of the welding current required for the base metal, current level required and any additional equipment features desired such as pulsation. Some power sources are capable of producing square-wave AC, which renders better arc performance than the conventional sine-wave AC. Some power sources have a pulsed-arc option. A pulsed arc first supplies a higher current pulse to the arc to achieve thorough fusion; a lower current pulse is subsequently supplied to prevent the electrode from overheating and melting. This lower current also prevents excessive melting of the base metal. Pulsed-arc current allows adjustments of the pulse current time, background current time, peak current level, and background current level to enable the creation of tailored wave forms that are best suited for particular applications.

The choice of polarity is important with direct current because the direction of current flow changes the how the thermal energy is distributed in the arc. DCEP heats the electrode much more than DCEN; thus, DCEP is rarely used except for very thin materials or for surfacing. When welding metals that have refractory oxide surfaces, such as aluminum and magnesium, oxide cleaning can take place in the electrode positive portion of the AC cycle because current flows from the base metal to the tungsten.

Some gas tungsten arc welding power sources also permit polarity adjustments. Adjustable polarity enables the modification of the alternating current in two ways—either by changing the proportion of time duration in the desired polarity, either electrode positive or electrode negative, or by adjusting the amplitude of the current in the desired direction. The greater the adjustment in the electrode positive current direction, the greater the oxide cleaning effected. It should be

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[7] American Welding Society (AWS) Committee on Filler Metals, *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*, AWS A5.12/A5.12M, Miami: American Welding Society.

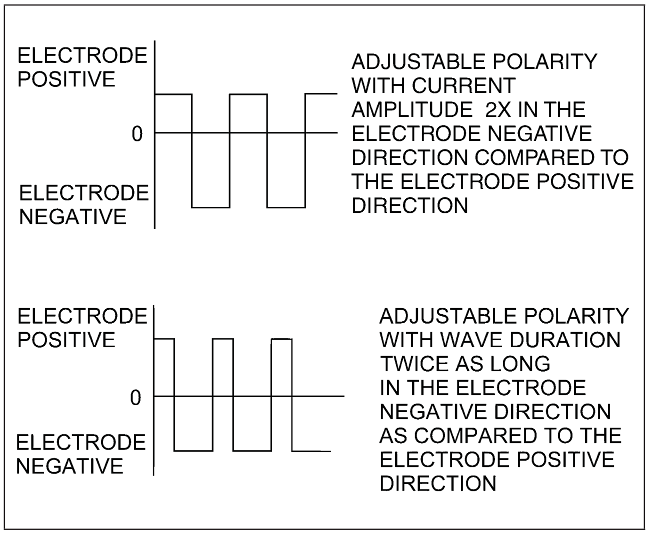


Figure 1.5—Square-Wave Alternating Current Adjustable Polarity Options

noted that polarity adjustments also result in additional heating of the tungsten electrode. Figure 1.5 illustrates these adjustable polarity options. Some newer power supplies have the ability to change frequencies of the alternating current cycle which can be used for multiple purposes and effects.

Gas tungsten arc welding can be done both with and without the addition of filler metal. Welds that are made without filler metal are called autogenous welds. For nonautogenous welding, filler metal can be added either manually or mechanically into the pool, where it is melted by the thermal energy of the molten pool. Care must be taken not to allow the filler metal rod to come into direct contact with the electrode, which would cause some of the filler to melt onto the tungsten electrode resulting in contamination. Techniques known as *hot-wire feed* and *cold-wire feed* are options of the mechanical feeding method. The hot-wire feed method involves preheating the filler metal through an external power source to minimize the thermal energy required by the molten weld pool to melt the filler metal, while the cold-wire technique involves no separate heating of the filler metal. The hot wire feed method increases the productivity of the process by increasing the deposition rate more than the cold-wire feed method.

A disadvantage of gas tungsten arc welding is its low relative productivity due to the lower travel speeds and deposition rates. Also, gas tungsten arc welding requires more skill, especially when manually feeding the filler metal, as both the torch and filler metal must be coordinated simultaneously. Mechanical wire feeding systems decrease the required skill level and somewhat increase process productivity.

The primary advantage of the GTAW process is its capability to join a wide variety of materials. Additionally, the process tends to be very stable and there is a greater control over heat input than with other welding processes resulting in an improved suitability for use on very thin materials. With respect to other arc processes, it is also easier to make radiographically clear welds.

Plasma Arc Welding

Plasma arc welding (PAW), illustrated in Figure 1.6, produces welds by striking a constricted arc between a nonconsumable electrode and the weld pool (transferred arc) or between the electrode and the constricting nozzle (nontransferred arc). The PAW process is very similar to the GTAW process, as it was a technological advancement based on the GTAW process. The process uses an inert shielding gas for almost all applications. Plasma arc welding lends itself to automated and robotic welding.

Though classified as a gas shielded arc process, plasma arc welding functions like a high power density process, as it has the capacity to join materials with the keyhole welding technique (see below) along with the conventional melt-in welding method (i.e., involving weld pools). A tungsten electrode is recessed in a nozzle that has a very small orifice through which the arc/gas plasma has been heated to an ionized condition, allowing the resulting plasma to carry electric current. This constricted orifice concentrates the arc and increases the exit velocity resulting in a well-defined, high power density plasma column. It is this aspect of the arc that makes the process function similar to a high-power-density process such as laser welding or electron beam welding. The PAW arc is stiffer and more stable than that used in gas tungsten arc welding because of the high velocity at which the plasma is propelled from the torch towards the workpiece. Thus, the PAW arc is less sensitive to the torch stand-off distance which is the between the nozzle and joint.

As illustrated in Figure 1.6, in both the transferred arc and nontransferred arc process variations, the tungsten electrode is connected to the negative terminal of the power supply. The positive terminal is connected to the workpiece in the transferred arc mode but it is connected to the orifice nozzle in the nontransferred arc variation. The constricted orifice concentrates the heat by producing a plasma jet with temperatures in the range of 30 000°F to 50 000°F (16 650°C to 27 760°C). This temperature is much higher than a typical open arc process which typically range from

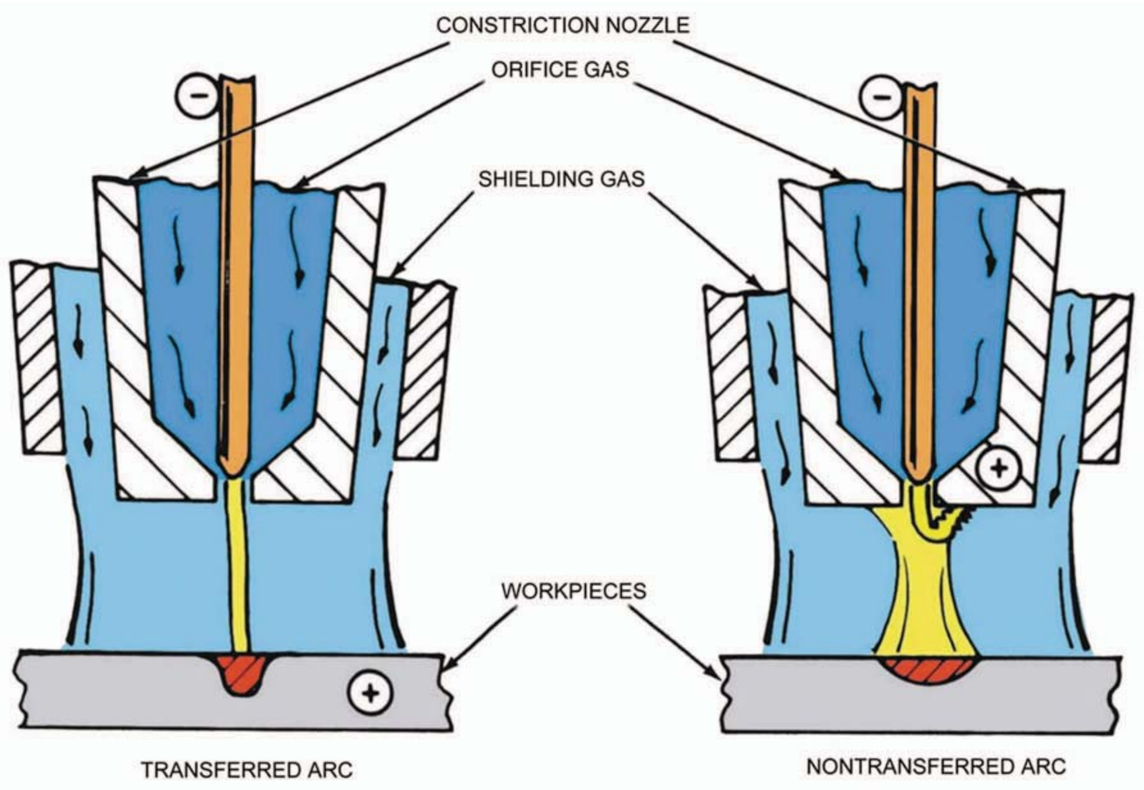


Figure 1.6—Schematic Illustration of Plasma Arc Welding: Transferred Arc (Left); Nontransferred Arc (Right)

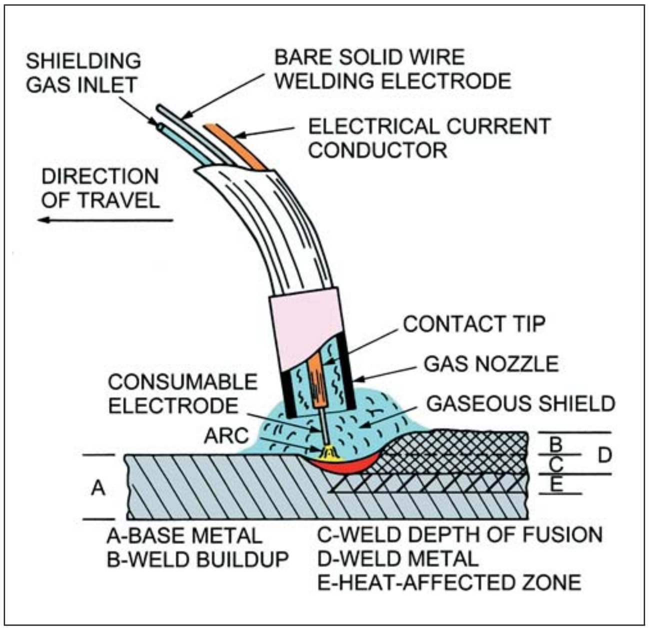
9000°F to 10 000°F (4980°C to 5540°C). Therefore, keyhole welding is possible in metal thicknesses up to 1/2 in. (12.7 mm) when implementing transferred arc plasma arc welding on a tightly fitted square butt joint. Thicker materials can be welded using the keyhole method when combined with a V- or U-groove through a portion of the joint thickness.

The keyhole technique results in excellent productivity because a high travel speed is required to maintain a stable keyhole. The high travel speed requires mechanization, precise joint location, and fit-up. In contrast, nontransferred arc plasma arc welding is used mostly for melt-in welding techniques, surfacing, and thermal spraying applications. It lends itself to manual control in many instances.

A low-power version of plasma arc welding, sometimes referred to as *microplasma arc welding*, is capable of welding materials as thin as 0.001 in. (0.025 mm). Much of this type of welding can easily be done manually.

Gas Metal Arc Welding

Gas metal arc welding (GMAW), often referred to colloquially as *MIG*, involves the use of an arc and consumable electrode with externally added shielding gas. In other parts of the world, the welding process is called MIG for metal inert gas, or MAG for metal active gas depending on the composition of the shielding gases used. With the various choices of metal transfer modes through the arc described below, the wide range of electrode sizes available, and the numerous shielding gas mixtures possible, the GMAW process can be used to weld many ferrous and nonferrous metals. These metals can range in size from 0.020 in. (0.51 mm) thin-gauge sections to any desired plate or pipe section thickness. With the proper procedure and technique, gas metal arc welding can be performed in all positions. If the variables are properly set on the controls of the welding machine then less skill is typically required for gas metal arc welding than for the SMAW or GTAW pro-



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.12.

Figure 1.7—Schematic Representation of Gas Metal Arc Welding

cesses. Figure 1.7 illustrates the gas metal arc welding process.

The shielding gas or gas mixtures used in gas metal arc welding are not completely inert unless welding aluminum or magnesium. Shielding gas generally consists of carbon dioxide, argon-carbon dioxide mixtures, argon-oxygen mixtures, or multiple gas blends. The mixed shielding gas blends typically result in smoother arc performance, less spatter, and promote enhanced wetting of the weld to the base metal. Most mixtures have been standardized and are commercially available in cylinders or bulk gas systems.

Gas metal arc welding employs either a solid electrode wire or an electrode with a core of powdered metal. A variety of ferrous and nonferrous alloys areavailable. Electrode sizes range from 0.020 in. to 0.062 in. (0.5 mm to 1.6 mm). Spool weights can vary from 1 lb to 60 lbs (0.5 kg to 27 kg), coils weigh from 50 lbs to 65 lbs (23 kg to 29.5 kg), and drums or bulk reels can weigh as much as 1000 lbs (450 kg). The unit cost of electrode wire usually varies inversely with the size of electrode and the weight of the spool, coil, or drum purchased. For example, the unit cost of a given alloy of 0.020 in. (0.5 mm) wire on a 1 lb (0.5 kg) spool may be more than five times higher than the unit cost of 0.062 in. (1.6 mm) wire purchased in a 1000 lbs (450 kg) drum. It is economically advisable to use the largest-sized electrode wire wound on the largest-sized spool, coil, or drum practical for the application.

One significant variable in any wire-fed arc process is the electrical stick out which is the distance between the contact tip and the work. This distance includes the length of wire extension past the contact tip as well as the height of the welding arc. The electrode is a very small conductor and therefore has high electrical resistance. The sensitivity to the effects of electrical stick out is affected by the bulk resistivity of the wire. Nickel and stainless steels have higher resistivity than aluminum and so the effect of the electrical stick out will be increased. If the extension of the electrode increases in a constant-voltage system, the current decreases rapidly because more current is used to preheat the electrode through resistive heating. The current is a function of wire feed speed and electrode extension. The current varies directly with wire feed speed but inversely with extension. However, deposition rate is a function of wire feed speed only because it is based on weld volume applied over time. If the wire feed is constant, the deposition rate is constant even though the current changes as the extension changes.

The basic equipment and accessories used in gas metal arc welding include a welding gun (air or water cooled); wire electrode; wire feeder; a power supply; shielding gas; cables and hoses; and in the case of water-cooled torches, a water circulation system. This process lends itself well to semiautomatic (manual), fully mechanized, automatic, and robotic welding. In semimechanized welding, the operator holds the welding gun, controlling the torch angles, extension, and travel speed along the joint. Alternatively, the gun can be mounted on a carriage with an adjustable speed control and moved along the joint at the desired travel speed.[8]

Several types of metal transfer variations can be used in gas metal arc welding, depending on a number of factors. These variations include the spray, globular, short-circuiting, pulsed-arc, and high-deposition, buried-arc metal transfer modes. Figure 1.8 summarizes these arc modes as a function of current density, illustrating their respective positions relative to one another. The type of shielding gas used also affects the metal transfer modes. For example, when using carbon dioxide, the resulting metal transfer is either short circuiting mode at lower current densities or the globular transfer mode at high current densities. True spray transfer mode cannot typically be achieved with 100% carbon dioxide shielding gas. The larger the electrode used, the higher the current required for a given current density.

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[8] For more information, see Chapter 9 of this volume.

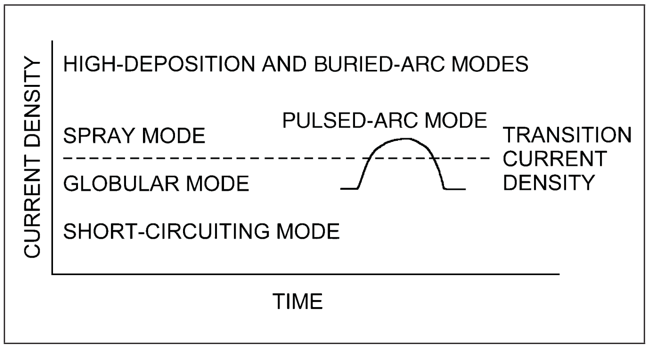


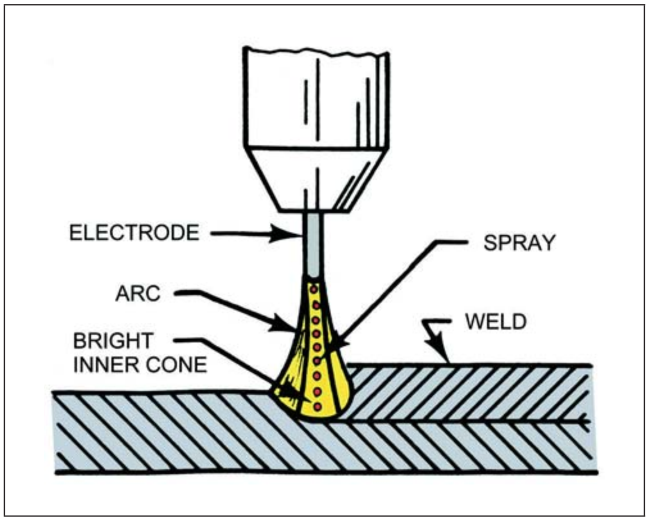
Figure 1.8—Gas Metal Arc Welding Transfer Mode Comparison

When the current density is increased above a point defined as the transition current density level, spray transfer mode is achieved. In spray transfer arc mode, the electrode metal is transferred as tiny droplets across a stiff, stable arc, as illustrated in Figure 1.9. The stable arc produces very little spatter. Argon should be predominant in the shielding gas mixture. Because this mode produces a high volume of molten metal at a high rate of speed, spray transfer is typically considered suitable for the flat and horizontal positions when using conventional CV power supplies. When using pulsed GMAW, spray metal transfer mode can sometimes be used in other welding positions.

Globular transfer mode, shown in Figure 1.10, is obtained when the current density is just below the transition current density level. When carbon dioxide is used as the shielding gas, globular transfer occurs even at high current density. The metal droplets formed at the end of electrode are larger in diameter than the electrode itself. With solid electrode wire, globular mode produces a rather erratic arc. In this case, the metal globules are propelled from randomly varying positions with respect to the center of the electrode tip. Substantial spatter results, producing a weld deposit that is rough and uneven. A more controlled version of this mode is used in flux cored arc welding (FCAW), an arc welding process using an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding gas from a flux contained within the tubular electrode, with or without additional shielding from an externally supplied gas, and without the application of pressure (refer to the section on flux cored welding).

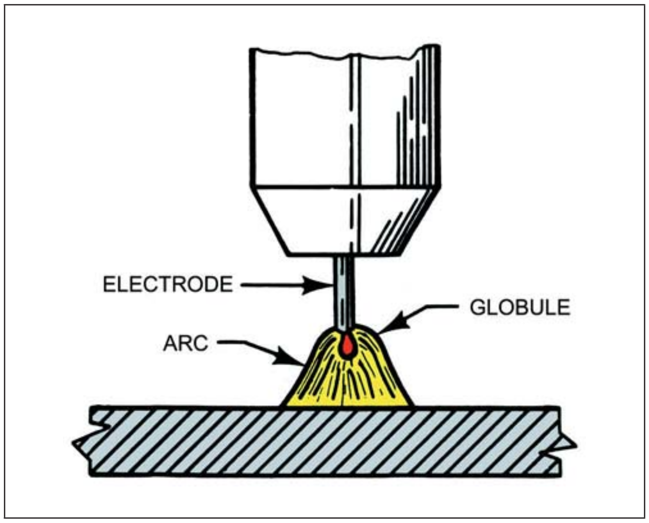
Short-circuiting transfer mode, which produces a characteristic crackling sound during welding, is obtained at the lowest range of current densities. The shielding gas mixture used in this mode, which can be applied in all welding positions, is typically rich in argon but can be 100% CO_2. It produces small, quickly solidifying welds suited to joining thin materials or bridging small root openings. In the latter case, this mode provides complete penetration and fusion to both members on the reverse side of an open root butt joint.

Figure 1.11 illustrates the short-circuiting metal transfer cycle. Position A shows the electrode prior to short cir-



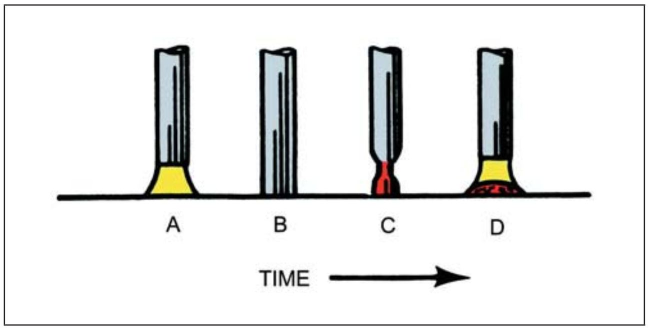
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.26.

Figure 1.9—Schematic Illustration of Spray Metal Transfer



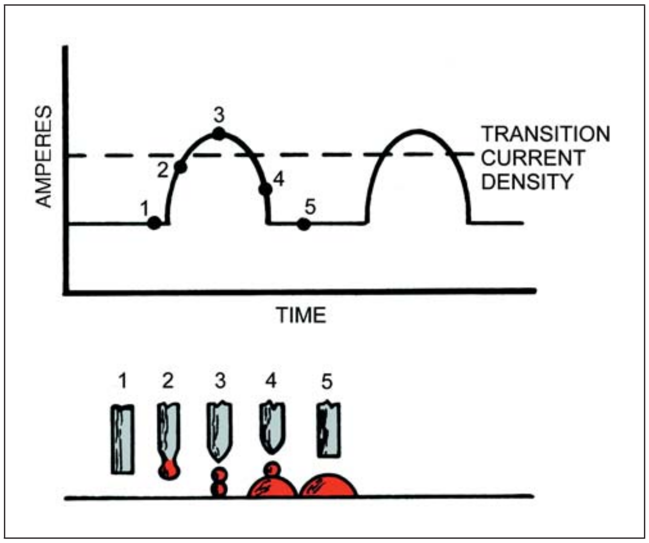
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.28.

Figure 1.10—Gas Metal Arc Welding: Globular Metal Transfer Mode



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.30.

Figure 1.11—Gas Metal Arc Welding: Short-Circuiting Metal Transfer Mode



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.30.

Figure 1.12—Gas Metal Arc Welding: Pulsed-Arc Mode

cuiting. The wire should be starting to melt prior to short circuiting and the droplet size should not be much greater than the diameter of the wire. Position B depicts the electrode short-circuiting to the weld pool, extinguishing the arc for an instant. Although this is not perceptible to the unaided eye, high-speed film has proven that the arc does indeed extinguish. Because of the short circuit, the globule is pinched off as the current peaks, as shown in position C. Position D shows the arc restored. This cycle can occur up to 200 times per second, depending on the electrical current and the shielding gas type used.

An important precaution must be observed when implementing the short-circuiting arc mode. Sufficient power must be used to obtain adequate fusion. For purposes of illustration, assume that a welder working with a section thicker than 1/4 in. (6.4 mm) is attempting to make a T-joint fillet weld traveling downhill using a 0.035 in. (0.9 mm) electrode at less than 100 A and 18 volts (V). The arc may sound as though it is working well under these operating conditions, but little if any fusion to the base metal is actually taking place because of insufficient power. Properly designed welding procedures must be carefully followed when operating in this mode.

Pulsed arc metal transfer mode (GMAW-P) is a metal transfer variation in which the welding current is pulsed. Shielding gases are generally composed of 90% or greater argon with a small addition of either CO_2 or oxygen. Figure 1.12 illustrates the behavior dynamics of the current with this mode. In Position 1, a low-background current is applied, prompting the formation of a small globule on the electrode. In Position 2, a pulse of current is about to cause the globule to separate from the electrode. In Position 3, the current has pulsed above the transition current density, and the droplet is transferred in spray metal transfer mode. The spray arc also applies heat, which aids fusion. In Positions 4 and 5, the current density is returning to the background current.

The advantages of the pulsed-arc mode include the option of using larger electrode sizes, greater process productivity, and enhanced fusion with a greater base metal mass (as compared to the short-circuiting mode). The pulsed-arc mode can also be used in all positions. However, GMAW pulsed-arc equipment is much more expensive than that used for the other arc modes. In addition, pulsed-arc background and peaking current amplitudes and durations must be properly adjusted for the electrode alloy type and size being used with a given shielding gas. Various manufacturers offer synergic systems using inverter power sources. Several pulsed-arc systems have microprocessor controls to synchronize the variables. A number of factory preset program options may be included. To improve performance during particular applications, provisions for changing any of the preset parameters are also available.

As illustrated (refer to Figure 1.8), the two metal transfer modes having the greatest current density are the buried-arc mode and the high-deposition-rate mode. The current densities of these modes may exceed 300 000 A/in.^{2} (465 A/mm^2) of the electrode cross-sectional area. At these densities, a 0.045 in. (1.1 mm) electrode feeds at about 1500 in./min (38 meters [m]/min). The voltage used in buried-arc mode is low enough to permit the arc to be below the surface of the metal, which produces a narrow, deep weld profile with a high crown or buildup. The high-deposition-rate mode utilizes a higher voltage, creating a wider weld profile that has less weld crown and is not as deep. The buried-arc and high-deposition-rate modes are normally implemented in fully mechanized or automatic gas metal arc welding.

Pulsed GMAW is no longer limited to the spray transfer mode. Computer technology and sensors have been developed to closely monitor the short circuiting process and respond dynamically to the process in near real time. For example, when a short circuit occurs, the current begins to increase due to the constant voltage power supply. In a standard GMAW process the current would continue to increase as the wire begins to melt and neck down in cross sectional area. This eventually ends in an explosive event as the short circuit is cleared and the arc is reestablished. In the pulsed short circuit mode, the power is controlled such that just prior to the short circuit being cleared, the power is temporarily turned off and the droplet is drawn into the weld pool by surface tension.

Once the droplet has detached from the wire, the power is switched back on and the arc is reestablished. There are several variations as to how this welding process adaptation is accomplished. The controls, algorithms and sensors used are independently developed by each of the manufacturers of the power supplies. Advantages can include spatter reduction, lower heat input, the ability to weld thinner gages of materials and the ability to control penetration.

There are several major advantages of gas metal arc welding. Foremost, the process can be used on a very wide range of metals and metal thicknesses, and is easier to learn and control than some of the other arc welding processes. The process is, by nature of the solid electrode, a low hydrogen welding process. Furthermore, the productivity is high due to the high deposition rates, the process is economically efficient because most of the wire used in the process is directly incorporated into the weld, and there is no loss from fluxes or the stub loss associated with SMAW.

However, there are also disadvantages to the GMAW process. Because the shielding is done with externally supplied gas, the process is sensitive to wind and weld quality can be impacted, and the process is less portable than shielded metal arc welding. Also, the welding arc is exposed during the process and those who are welding or may be exposed to the arc need to be adequately protected from the light intensity and UV exposure.

Flux Cored Arc Welding

Flux cored arc welding (FCAW) uses the same type of power sources, wire feeders, and welding guns as gas metal arc welding. However, FCAW incorporates the use of a tubular electrode with a core containing flux and alloying elements. A variation, self-shielded flux cored arc welding (FCAW-S), obtains its shielding gases from the breaking down of the internal flux component of the electrode as it is consumed by the arc. The FCAW-S gun differs from the GMAW gun in that it has no nozzle for shielding gas. Figure 1.13 illustrates both gas shielded and FCAW-S. Gas shielded flux cored arc welding (FCAW-G) is another variation of the process.

For self-shielded flux cored electrodes, the flux in the electrode core serves the same functions as the coating on the shielded metal arc electrode. It helps initiate and stabilize the arc and contains deoxidizers, additional alloying elements, scavengers, slag, and vapor-forming ingredients sufficient to provide necessary protection from the atmosphere. Self-shielded flux cored arc welding is suited to outdoor work in windy conditions in which externally added shielding gases would be blown away. Electrodes are marketed for carbon steels and some alloy steels. Gas-shielded flux cored arc electrodes must be supplemented by externally added gas, typically carbon dioxide. Electrode sizes range from less than 0.020 in. to 0.16 in. (0.5 mm to 4 mm).

The FCAW process can require more electrode extension than gas metal arc welding. If the extension is too short, the vapor-forming ingredients are not sufficiently heated to generate enough arc vapor for adequate shielding, potentially resulting in porosity in the weld. Some FCAW-S electrodes require even greater extension than FCAW-G electrodes.

Deposition rates in FCAW can be somewhat higher than those attained with gas metal arc welding in spite of less cross sectional area of the tubular wire when compared to the solid steel wire of the same diameter. With a given electrode size and current, the current density is also higher with flux cored electrodes than with the electrodes used for gas metal arc welding. This increased current density occurs because flux cored electrodes are tubular rather than solid, and the flux core is made up of metallic and nonmetallic ingredients that have a lower current-carrying capacity than solid metal. The slag ingredients have a protective effect on the molten weld pool because the molten slag floats on top of the molten metal. Some slag systems freeze prior to weld solidification while others solidify after the weld metal. Fast solidifying slags enable welding out of position because these slags act like a dam to hold the molten metal in place until it solidifies. The weld pool surface is typically very dynamic when this slag freezes and will result in a noticeable ripple pattern. The slower solidifying slags will result in welds with little to no ripple because the molten welds have an opportunity to calm some under the molten slag prior to the metal solidifying. The controlled globular transfer typical with FCAW allows for a broad range of electrical variables, which contributes to improved operating characteristics.