Welding Handbook

Ninth Edition

Volume 1

WELDING SCIENCE AND TECHNOLOGY

Prepared under the direction of the
Welding Handbook Committee

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Editors

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The *Welding Handbook* is the result of the collective effort of many volunteer technical specialists who provide information to assist with the design and application of welding and allied processes.

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PREFACE

Welding Science and Technology is Volume 1 of the ninth edition of the American Welding Society's *Welding Handbook* series. This volume presents an overview of the most recent research and engineering developments in the field of welding science and technology. Volumes 2 and 3 of the ninth edition address welding processes, whereas Volumes 4 and 5 address materials and applications. Together, the five volumes of the ninth edition substantially expand upon and update the information presented in the four volumes of the *Welding Handbook,* eighth edition.

This volume features seventeen chapters covering the fundamentals of welding, cutting, joining, and allied processes. Four chapters discuss metallurgy, the physics of welding and cutting, heat flow in welding, and residual stress and distortion. Other important chapters discuss the engineering considerations of weld design, weldment tooling and positioning, automation, process monitoring and control (new in this volume), 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 included. Two useful appendices present a glossary of standard welding terms and a guide to metric practice for the welding industry. 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. Additional sources are suggested in the Supplementary Reading List at the end of each chapter. For easy access to specific topics, a table of contents for each chapter is presented on the cover page, and a subject index with cross-references appears at the end of the volume. A major subject index of this volume and previous editions of the *Welding Handbook* is included to direct the reader to the volume and chapter of interest.

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. The Chapter Committee members and the Welding Handbook Committee member with responsibility for the chapter are recognized on the cover pages of the chapters. An important contribution to this volume is the review of each chapter provided by members of the American Welding Society's Technical Activities Committee (TAC) and other specialists.

The Welding Handbook Committee welcomes your comments and suggestions. Please address them to the Editor, Welding Handbook, American Welding Society, 550 N.W. LeJeune Road, Miami, Florida 33126.

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Welding Handbook Committee
1999–2001

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CHAPTER 1

SURVEY OF JOINING, CUTTING, AND ALLIED PROCESSES

INTRODUCTION

This chapter introduces the conventional and more widely known 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 arc, resistance, and solid-state welding processes as well as brazing, soldering, and adhesive bonding. The cutting processes examined include thermal and nonthermal methods. The thermal spraying processes considered include flame and plasma arc spraying as well as arc and detonation flame spraying.

With respect to process selection, as several processes may be applicable for a particular job, the challenge lies in selecting the process that is most suitable in terms of fitness for service and cost. However, these factors may not be compatible, thus forcing a compromise. The selection of a process ultimately depends on several criteria. These include the number of components to be fabricated, capital equipment costs, joint location, structural mass, and the desired performance of the product. The adaptability of the process to the location of the operation, the type of shop, and the experience and skill levels of the employees may also have an impact on the final selection. These criteria are examined as they relate to the various joining, cutting, and thermal spraying processes.

As this chapter is intended to serve merely as a survey of the most common joining, cutting, and thermal spraying processes,[1] 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 take into account safety and health considerations such as those presented in the American National Standard *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1,[2, 3] and the information provided in the manufacturers' material safety data sheets (MSDSs). 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,*[4] Volume 2 of the American Welding Society's *Welding Handbook*, 8th edition, presents in-

1. For further information on the categorization of the welding, joining, cutting, and allied processes, see Appendix A.
2. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. American National Standards Institute (ANSI) Committee Z49 on Safety in Welding and Cutting, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1, Miami: American Welding Society.
4. O'Brien, R. L., ed., 1991, *Welding Processes*, Vol. 2 of *Welding Handbook*, 8th ed., Miami: American Welding Society.

depth coverage of each of the welding, cutting, and allied processes.

JOINING PROCESSES

The goal of the joining processes is to cause diverse pieces of material to become a unified whole. In the case of two pieces of metal, when the atoms at the edge of one piece come close enough to the atoms at the edge of another piece for interatomic attraction to develop, the two pieces become one. Although this concept is easy to describe, it is not simple to effect. Surface roughness, impurities, fitting imperfections, and the varied properties of the materials being joined complicate the joining process. Welding processes and procedures have been developed to overcome these difficulties by incorporating the use of heat or pressure, or both. Though portions of this description do not apply to brazing, soldering, and adhesive bonding, an explanation will be given when these processes are described later in the chapter.

Barring a few exceptions, most welding processes apply significant heat to the base material. This heat is only a means to bring the atoms at the edge of one piece of material close enough to the atoms of another piece for interatomic attraction. However, this heat is detrimental to the microstructure of the materials being joined. As hot metal tends to oxidize, sufficient protection from oxidation must be provided by the welding process to prevent this detrimental reaction with ambient oxygen. Some metals are far more sensitive than others, in which case protection from oxidation becomes more demanding. Thus, while examining each welding process, the reader should consider whether heat is produced by the process and, if so, the manner in which it is produced. The means by which sufficient protection against oxidation is provided by the process should then be identified.

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

1. Availability and fitness for service;
2. Skill requirements;
3. Weldability of the base metal alloy with respect to type and thickness;
4. Availability of suitable welding consumables;
5. Weld joint design;
6. Heat input requirements;
7. Demands of the welding position;
8. Cost of the process, including capital expenditures, materials, and labor;
9. Number of components being fabricated;
10. Applicable code requirements; and
11. 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 usually 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. Nonetheless, Table 1.1 serves as a useful tool in providing general guidelines for the screening and selection 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 but may utilize a filler metal. The arc is struck between the workpiece and the tip of the electrode. The intense heat produced by the arc quickly melts a portion of the base metal, resulting in the formation of a weld. The arc welding processes may be moved along the joint to produce the weld or held stationary while the workpiece is moved under the process.

Arc welding operations are performed by conducting the welding current through consumable electrodes, which take the form of a wire or rod, or nonconsumable electrodes, consisting of carbon or tungsten rods. Metal arc processes utilize consumable electrodes that combine electrode filler metal with the molten base metal to create the weld. They may also produce a slag covering to protect the molten metal from oxidation. The nonconsumable arc processes can generate a weld by melting the base metal only, resulting in what is termed an *autogenous weld*. If filler metal is required in a nonconsumable process, it may be fed either manually or mechanically into the molten weld pool. In this case, the nonconsumable electrode serves only to sustain the arc.

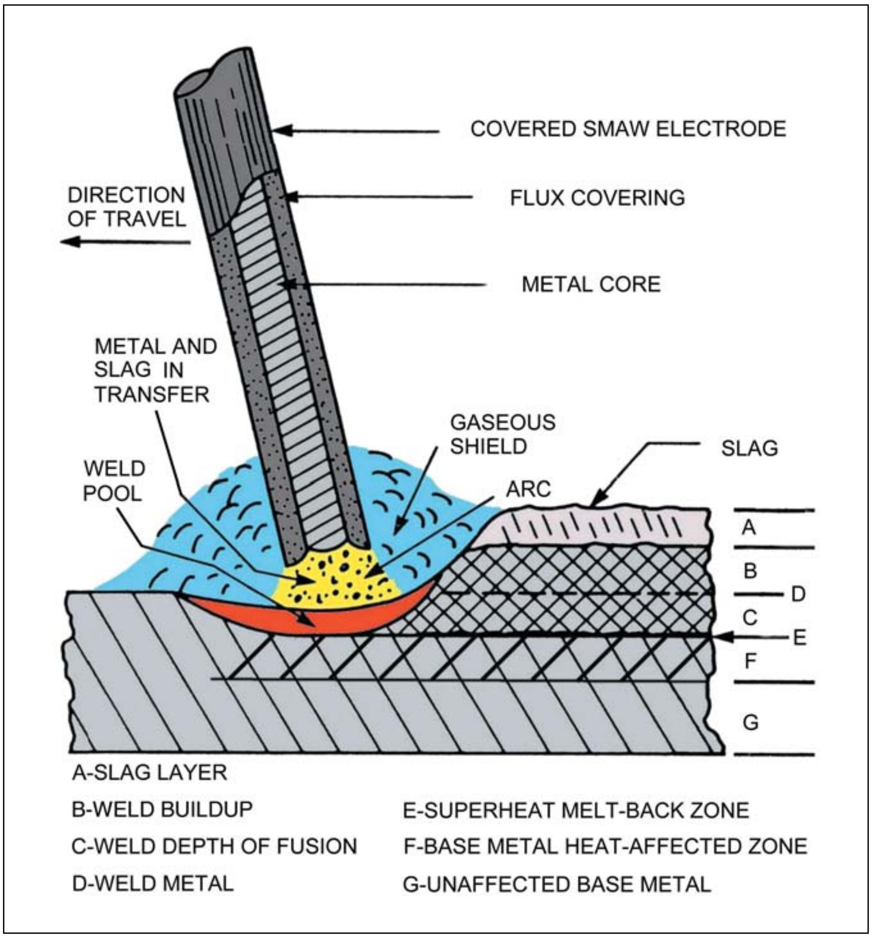
Shielded Metal Arc Welding

Illustrated in Figure 1.1, shielded metal arc welding (SMAW) is a basic, versatile process used to weld ferrous and some nonferrous metals. The most widely known of the arc welding processes, shielded metal arc welding is sometimes referred to colloquially as *stick*

Table 1.1
Capabilities of the Commonly Used Joining 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
		Processes*																						
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	x	x	x
	I	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	
	T	x		x				x	x		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																							

* 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; and S = soldering.
† S = sheet (up to 1/8 inch [in.] 3 millimeters [mm]); I = intermediate (1/8 in. to 1/4 in. [3 mm to 6 mm]); M = medium (1/4 in. to 3/4 in. [6 mm to 19 mm]); T = thick (3/4 in. [19 mm] and up).
‡ Commercial process.
§ Copper requires molybdenum-coated tips.



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

welding or simply *arc welding*. This process, which is applied without pressure, 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 consists of a wire core around which a concentric mixture of silicate binders and powdered materials such as fluorides, carbonates, oxides, metal alloys, 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.[5]

5. An excellent guide to the classification of shielded metal arc welding 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,* ANSI/AWS A5.1, Miami: American Welding Society.

Generically, the qualifier *shielded metal arc* could be used to describe a number of arc processes. 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.

The bare section of the electrode is clamped into an electrode holder, which, in turn, 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. The heat of the arc melts the base metal in the immediate area 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 came into existence during the latter part of the nineteenth century, welding was hindered by the less-than-ideal electrical power sources available and the fact that a bare metal rod served as the consumable electrode. This bare metal electrode made it very difficult to initiate and maintain an arc. Moreover, because the bare electrode provided no protection from the atmosphere, the resulting weld had poor properties.

Coverings for welding electrodes were developed in the 1920s and have undergone improvements in terms of formulation and production ever since. These improvements have resulted in ease of arc initiation and operation as well as excellent weld properties. The ingredients in the coatings perform a number of functions. They stabilize the arc, thereby rendering excellent operation performance. They produce (1) shielding vapors, which displace air; (2) deoxidizers and other scavengers that purify the weld; and (3) slag, which provides a physical protection or "lid" over the hot weld metal. Electrode coatings that incorporate powdered metal increase the deposition rate potential and enable the operator to drag the electrode lightly instead of having to maintain a proper arc length manually. This reduces 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. (2 millimeters [mm] to 8 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 coated with metal powder, 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.

While smaller electrodes cannot successfully conduct high currents, they are able, at a certain point, to maintain high current density. A point is reached at which small electrodes sustaining high current densities yield higher deposition rates than larger electrodes with lower current density. For this reason, other welding processes that utilize a continuous wire feeder often render greater productivity. They use an electrode that is much smaller in diameter, which can sustain much higher current density than shielded metal arc welding electrodes.

The application of the shielded metal arc welding process involves relatively high labor costs. 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 a number of factors. These include the discarding of electrode stubs when the electrode is consumed to within 2 in. to 3 in. (50 mm to 75 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 and the interruptions of the work required to change electrodes and remove the slag from the weld after each pass.

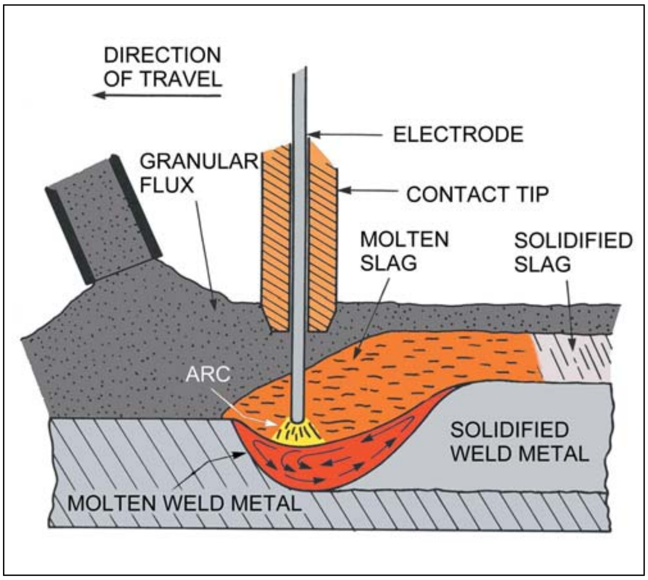
The equipment used in shielded metal arc welding is the simplest and least expensive of that used for the electric welding processes. The necessary components are a power source of adequate current rating and duty cycle, suitably sized electrical cables, an electrode holder, and a workpiece-lead clamp. 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, shielded metal arc welding operators must wear sturdy dry clothing and leather gloves for protection against spatter and electric shock. A helmet equipped with a dark lens shields the eyes from the brilliance of the arc, electromagnetic radiation, and flying slag particles.

The shielded metal arc process offers several other 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, shielded metal arc welding has wide application in the construction, pipeline, and maintenance industries, among others.

Submerged Arc Welding

A versatile production welding process, submerged arc welding (SAW) effects the joining of metals by heating them with an arc formed between a bare metal electrode and the workpiece. Illustrated in Figure 1.2, this process involves submerging the welding arc beneath a mound of granular flux particles as the arc is initiated. Additional flux is continually added in front of the electrode as weld travel progresses. The flux protects the arc and molten weld metal from ambient atmosphere, thereby preventing the formation of oxides. The arc quickly melts some of the flux and base metal but remains covered by a combination of melted and



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

unmelted flux. Therefore, the arc is invisible. Typically, the ratio of flux to electrode used is 1 pound (lb) to 1 lb.

Used extensively in pipe manufacturing, pressure vessel fabrication, and ship building, submerged arc welding is most widely employed in the welding of many grades of carbon, low-alloy, and 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 adaptable to automated and robotic applications.

The welding positions best suited for submerged arc welding are the flat position for fillet and groove welds (1F and 1G) and the horizontal position for fillet welds.[6] A modification to the process involving the use of special flux shelves can facilitate welding butt joints in the horizontal position (2G). The vertical and overhead welding positions cannot be utilized in submerged arc welding since gravity is a factor in maintaining the flux covering of the arc and molten pool.

The electrodes used in submerged arc welding consist of coiled wire that feeds into the arc. These electrodes are usually supplied in coils or drums. For larger jobs, the larger-sized packages maximize economy by increasing operating efficiency and decreasing electrode unit costs. The electrode diameters usually specified in submerged arc welding range between 1/16 in. and 1/4 in. (1.5 mm and 6 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 mm). However, reduced current and 0.045 in. (1 mm) or smaller electrode wire are sometimes used for welding thicknesses below 1/4 in. (6 mm).

The flux used in submerged arc welding can be selected in combination with the electrode filler metal to yield specific weld qualities. Various filler metal-flux combinations produce beneficial chemical reactions and modify the chemical composition of the weld metal. The flux may contain ingredients that contribute alloying additions to the weld metal. The unmelted flux can be vacuumed from the completed weld and reused once any lumps of slag have been sifted out of it. 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 slows the cooling rate and produces a wider base metal heat-affected zone (HAZ). This is not acceptable for metal alloys that require high toughness values or faster cooling rates to minimize the HAZ degradation of a tempering treatment. Adjustments carried out to decrease heat input in the procedure may help. These include decreasing the amperage and voltage or increasing the travel speed.

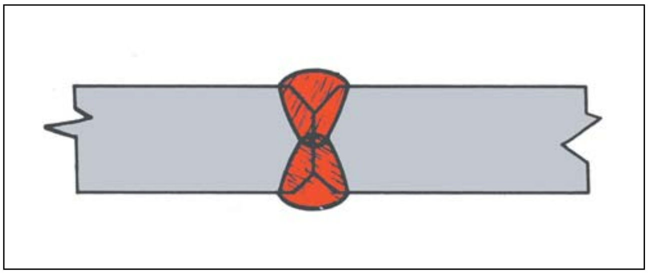
Both mechanized and semimechanized forms of submerged arc welding are used extensively in industrial applications. With mechanized submerged arc welding, a combination of multiple electrodes and cold wires (wires not heated by another source) can be used for high productivity and penetration control. Surfacing[7] with a modification of submerged arc welding is performed with a metal strip-type electrode supplemented by a cold strip feeding into the deposit. This results in a wide deposit, minimal penetration, and a high deposition rate.

High current densities are possible with submerged arc welding since the flux has a tranquilizing effect on the arc. High current densities yield high deposition rates and deep penetration, the latter of which minimizes the area required for the weld joint. High deposition rates and deep penetration with minimal joint area all complement each other, rendering high productivity. In addition, the depth-to-width ratio of the welding may be critical in some alloys to prevent centerline cracking in the weld. Figure 1.3 illustrates this type of joint.

Submerged arc welding can also be carried out with relatively low current densities. In this case, deposition rates and penetration are correspondingly low. Electrical parameters and the travel speed along the joint can

6. Welding positions are illustrated in Appendix A.

7. For additional information about surfacing, refer to Chapter 7 in Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of *Welding Handbook*, 8th ed., Miami: American Welding Society.



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 Produced by Submerged Arc Welding

be adjusted to produce a variety of welds, ranging from a wide, flat deposit with little penetration to a deep, narrow weld with a high crown or buildup. Alternating current, direct current electrode positive (DCEP) and direct current electrode negative (DCEN) can be used.

Though single-electrode welding is the most common configuration used in submerged arc welding, two arcs may also be used simultaneously in a procedure known as the *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 (the deflection of an arc from its normal path by magnetic fields) are achieved using ac on the second electrode. Offering high deposition rates, the tandem arc process is used in mechanized and automated welding to join materials whose thickness is 1/2 in. (12 mm) or greater. As many as five electrodes feeding into the same weld pool can be used.

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. Users should avoid breathing the dust generated when pouring or otherwise handling flux. As certain elements can be hazardous when vaporized, the manufacturer's material safety data sheets (MSDSs) should be consulted to identify potentially hazardous materials.

Gas Tungsten Arc Welding

The gas tungsten arc welding (GTAW) process, often referred to colloquially as *TIG welding*, incorporates the use of a nonconsumable tungsten electrode to sustain the arc, which is shielded from the atmosphere by externally added gas. Gas tungsten arc welding is the most versatile of the arc processes. Welds can be made with or without filler metal, and very thin materials of just a few thousandths of an inch (less than 1 millimeter) can be welded. Gas tungsten arc welding can be used in all welding positions to join just about all weldable ferrous and nonferrous alloys.

Gas tungsten arc welding can be used in automated or robotic applications. Weld control is excellent because the welder can establish a molten pool and then add filler metal as desired. This excellent control yields exceptional fusion and wetting at the beginning of the weld, thus avoiding incomplete fusion, which can take place initially when using consumable electrode processes. Figure 1.4 illustrates the gas tungsten arc process.

The shielding gas utilized in gas tungsten arc welding is usually, though not always, inert (i.e., it does not participate in chemical reactions). Argon is the predominant shielding gas used, though helium and argon-helium mixtures are sometimes utilized to obtain greater weld penetration. Inert gas shielding displaces the ambient atmosphere so that welding can take place in a nonreactive atmosphere. Although the inert gas prevents detrimental reactions, some beneficial reactions are also inhibited. For this reason, reactive gases such as hydrogen or nitrogen are sometimes mixed with the inert gas to obtain the desired effect. As the tungsten electrode may react unfavorably with certain shielding gases, the choice of shielding gases that can be used with this process is limited.

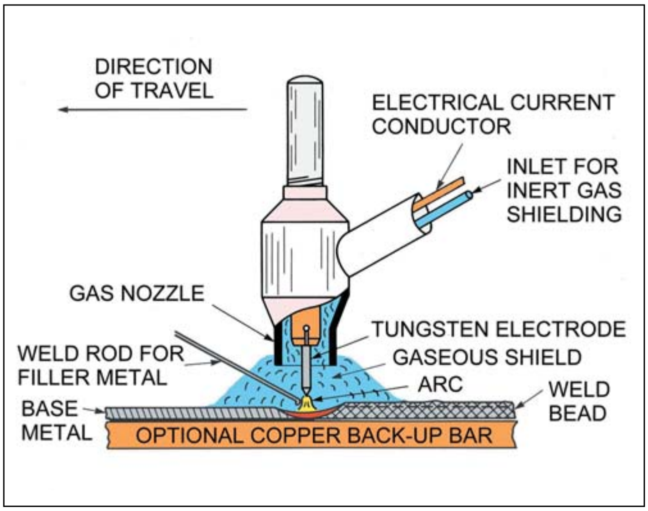


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding

Tungsten electrodes are often alloyed with small amounts of oxides from other elements. One widely used tungsten electrode contains 2% thorium oxide (thoria), which enhances electron emission and thus provides the electrode a higher current-carrying capacity without inducing melting. Oxides of other elements that are available in electrodes include cerium, lanthanum, and zirconium. The American Welding Society (AWS) standard *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*, AWS A5.12/A5.12M,[8] 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 type of welding current required for the application. 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 provide a current output wave pattern suited to a particular application.

The choice of polarity is important as well. DCEP heats the electrode much more than DCEN; thus, DCEP is rarely used. This is unfortunate, considering the effectiveness of the oxide cleaning that takes place from the surface of the base metal when the current flows in direction from the base metal to the tungsten, as is the case when the electrode is DCEP. When welding metals that have refractory oxide surfaces (i.e., surfaces that protect the base metal against oxidation) such as aluminum and magnesium, oxide cleaning can take place in the electrode positive portion of the ac cycle.

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 direction (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 noted, however, that polarity adjustments also result in additional heating of the tungsten electrode. Figure 1.5 illustrates these adjustable polarity options.

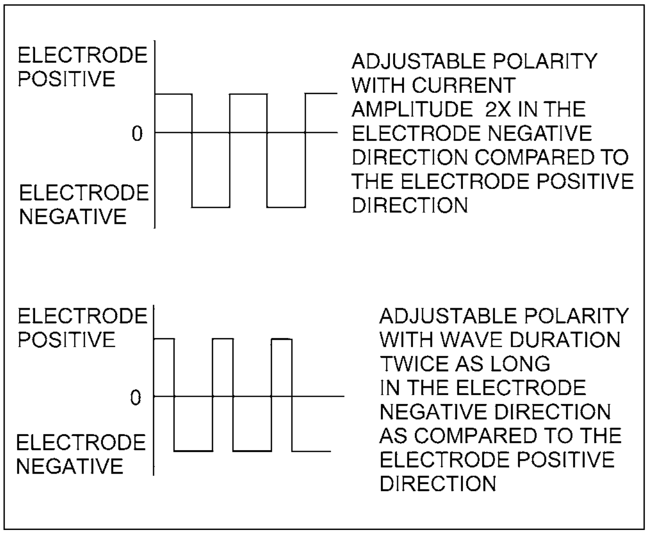


Figure 1.5—Square-Wave Alternating Current Adjustable Polarity Options

Autogenous welds can be produced by melting and fusing the base metal edges together without adding filler metal. However, filler metal can be added 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 arc, which would cause it to be quickly drawn onto the tungsten electrode, thereby contaminating it. 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 to minimize the thermal energy required by the pool to melt it. The cold-wire technique involves no 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.

The greatest disadvantage of gas tungsten arc welding is its low productivity. Consumable electrode arc processes produce welds at a much faster rate because the electrical power heats the filler metal directly. In addition, the current density used with the consumable electrode processes is much higher. For example, gas tungsten arc welding with a 1/16 in. (1.6 mm) tungsten electrode and a typical current of 100 amperes (A) yields a current density of 32,250 A/in.^{2} (53 A/mm^2). In contrast, gas metal arc welding (see below) with a consumable electrode of the same size and the typical current of 300 A results in a current density of 96,770 A/in.^{2} (158 A/mm^2). The higher current density employed in gas metal arc welding requires that the filler metal electrode be fed into the arc at a rapid rate, resulting in

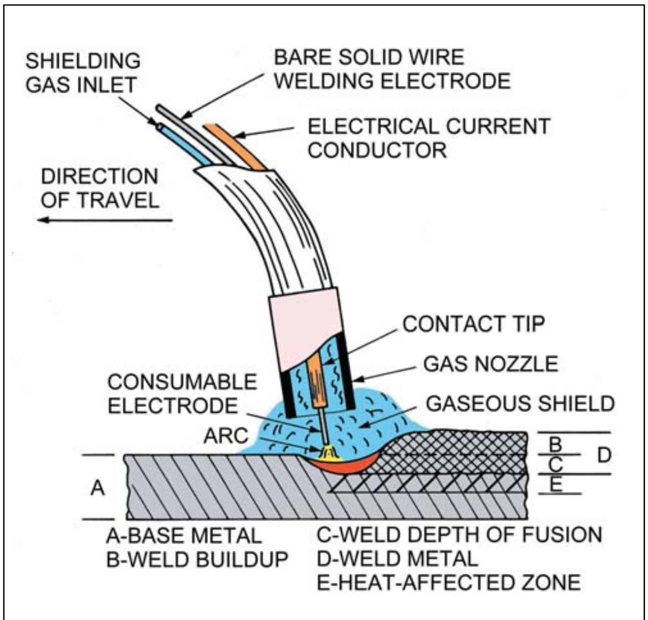
8. American Welding Society (AWS) Committee on Filler Metals, *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*, AWS A5.12/A5.12M, Miami: American Welding Society.

a weld deposit time that is much faster than that achieved with gas tungsten arc welding.

Gas tungsten arc welding also requires great 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. Nonetheless, welders who master gas tungsten arc welding become enamored of its versatility.

Gas Metal Arc Welding

Gas metal arc welding (GMAW), often referred to colloquially as *MIG* or *wire feed welding,* involves the use of a metal arc and consumable electrode with externally added shielding gas. With the various choices of arc modes 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. (0.5 mm) thin-gauge sections to any desired plate or pipe section thickness. With the proper procedure, welding can be performed in all positions. If the variables are properly balanced, less skill is required for the gas metal arc welding than for the SMAW or GTAW processes. Figure 1.6 illustrates the gas metal arc welding process.



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

Figure 1.6—Schematic Representation of Gas Metal Arc Welding

The shielding gas or gas mixture used in gas metal arc welding is often not completely inert. Shielding gas may often consist of carbon dioxide alone, carbon dioxide mixed with argon, or carbon dioxide mixed with several gases. Small quantities of oxygen (up to 5%) are sometimes mixed with the argon. If properly blended, these mixtures result in smoother arc performance, less spatter, and enhanced wetting (i.e., spreading and adhering) of the weld to the base metal. Some mixtures have been standardized and are commercially available in cylinders.

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 are available. Electrode sizes range from 0.020 in. to 0.125 in. (0.5 mm to 3.2 mm). Spool weights vary from l lb to 60 lb (0.5 kg to 27 kg), whereas coils weigh from 50 lb to 65 lb (23 kg to 29.5 kg), and drums, up to 1000 lb (450 kg). The unit cost of electrode wire 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 0.125 in. (3 mm) wire purchased in a 1000 lb (450 kg) drum. Therefore, 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 distance the electrode protrudes past the end of the contact tip to the work, termed *electrode extension.* The electrode is a very small conductor and therefore has high electrical resistance. If the extension of the electrode increases even a fraction of an inch in a constant-voltage system, the current decreases rapidly because more current is used to preheat the electrode. The current is a function of wire feed speed and electrode extension. The current varies directly with wire feed speed but inversely with extension. The deposition rate, on the other hand, is a function of wire feed speed only; therefore, 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); electrode; an electrode feed unit; welding control; 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 semimechanized, fully mechanized, automatic, and robotic welding. In semimechanized welding, the operator holds the welding gun, controlling its attitude, 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.[9]

9. For additional information, see Chapter 11, "Mechanized, Automatic, and Robotic Welding."

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 and buried-arc metal transfer modes. Figure 1.7 summarizes these arc modes as a function of current density, illustrating their respective positions in relation to one another. The type of shielding gas used also affects the arc modes. For example, when using carbon dioxide, the resulting metal transfer is characteristically globular even at high current density. The larger the electrode used, the higher the current required for a given current density.

Spray transfer mode is activated when the current density level rises above the transition current density level, which is defined as the current density level above which spray transfer occurs. The transition current density level is identified as a dotted line in Figure 1.7. In spray transfer arc mode, the electrode metal is transferred as tiny droplets across a stiff, stable arc, as illustrated in Figure 1.8. The stable arc is rather quiet and 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 considered suitable for the flat and horizontal positions only.

Globular transfer mode, shown in Figure 1.9, 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 (see below).

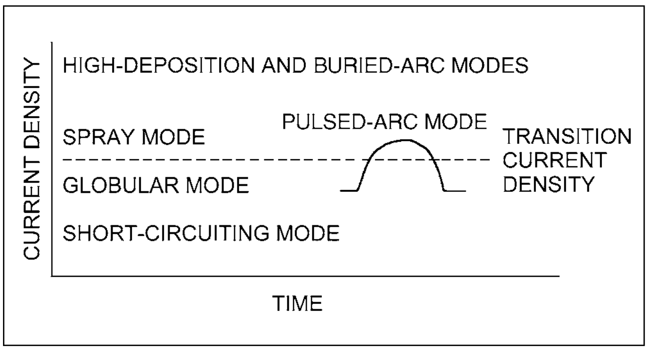
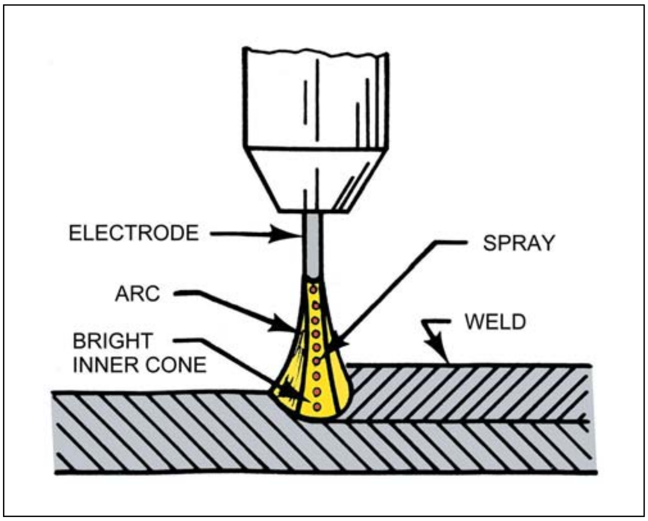
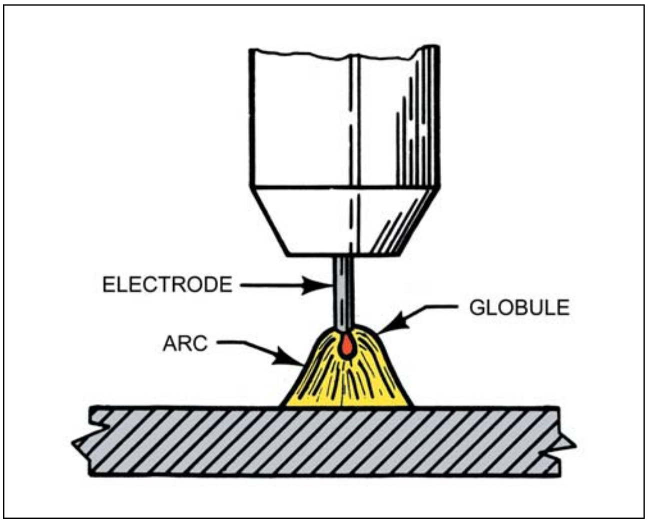


Figure 1.7—Gas Metal Arc Welding Transfer Mode Comparison



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

Figure 1.8—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.

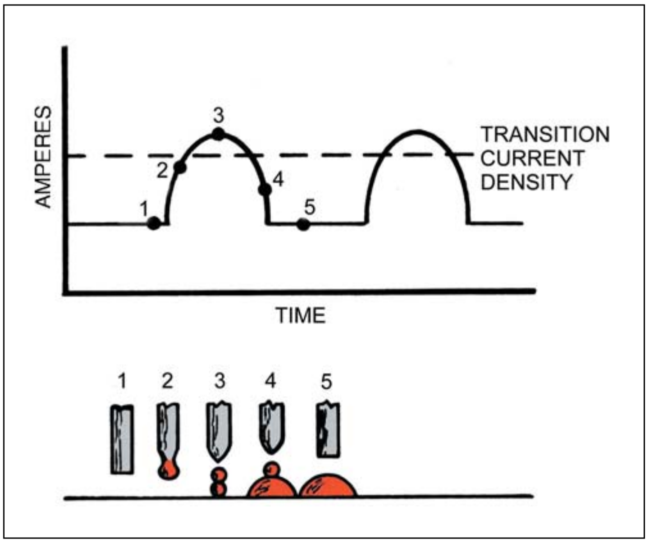
Figure 1.9—Gas Metal Arc Welding: Globular Metal Transfer Mode

Short-circuiting transfer mode, which has a characteristic buzzing sound, 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. It produces small, quickly solidifying welds suited to joining thin materials or bridging root openings. In the latter case, this mode provides full penetration and fusion to both members on the reverse side of an open root butt joint.

Figure 1.10 illustrates the short-circuiting metal transfer cycle. Position A shows a globule forming on the electrode tip just before being freed. Position B depicts the globule 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 gas parameters used.

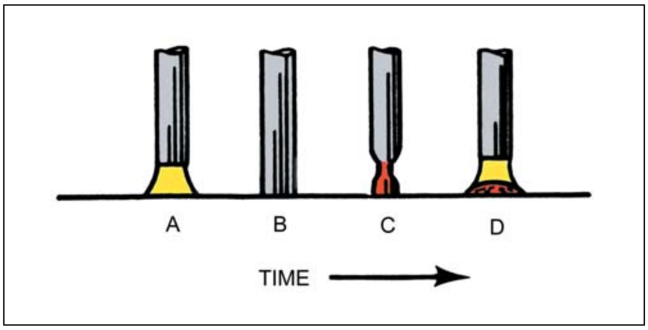
An important precaution must be observed when implementing the short-circuiting arc mode. Sufficient power must be used to obtain thorough fusion as soon as the mass of the base metal becomes critical. For purposes of illustration, assume that a welder working with a section thicker than 1/4 in. (6.4 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. Argon typically predominates in the shielding gas mixture. Figure 1.11 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.



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: Pulsed-Arc Mode



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

Figure 1.10—Gas Metal Arc Welding: Short-Circuiting Metal Transfer Mode

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 in Figure 1.7, the two metal transfer modes having the greatest current density are the buried-arc and high-deposition-rate modes. 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 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.

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, flux cored arc welding incorporates the use of a tubular electrode with a core containing flux. A variation, self-shielded flux cored arc welding (FCAW-S), obtains its shielding gases from the electrode and requires no externally added gas. The self-shielded flux cored arc welding gun differs from the GMAW gun in that it has no nozzle for shielding gas. Figure 1.12 illustrates both gas shielded and self-shielded flux cored arc welding. Gas shielded flux cored arc welding (FCAW-G) is another variation.

The flux in the electrode core serves the same functions as the coating on the shielded metal arc electrode. It stabilizes the arc and contains deoxidizers, scavengers, slag, and vapor-forming ingredients. Gas-shielded flux cored arc electrode fluxes must be supplemented by externally added gas, typically carbon dioxide. Self-shielded arc electrodes provide enough slag, vapors, and deoxidizers 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. Electrode sizes range from less than 0.020 in. to 0.16 in. (0.5 mm to 4 mm).

Flux cored arc welding requires 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. Inadequate arc vapor can cause porosity in the weld. Some self-shielded flux cored arc welding electrodes require even greater extension than gas shielded flux cored arc welding electrodes.

Deposition rates in flux cored arc welding are somewhat higher than those attained with gas metal arc welding. 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 has less density and current-carrying capacity than metal. The slag ingredients have a somewhat tranquilizing effect on the weld pool, which allows for high current density and minimal spatter. The controlled globular transfer typical with flux cored arc welding allows for a broad range of electrical variables, which contributes to good operating characteristics.

The presence of flux as part of the process enables beneficial chemical reactions as does the coating ingredients on the SMAW electrode. However, the productivity potential is significantly higher than with SMAW due to the high current density used with this process and the fact that it is not necessary to stop to change electrodes as often. Flux cored arc welding has a rather large window of operating variables as compared to gas metal arc welding, but the process efficiency is lower than that in gas metal arc welding due to slag ingredients that aid in protection from the atmosphere but do not become weld metal. With the gas-shielded process, the shielding gas is easily blown away by air drafts, as it would be with gas metal arc welding. However, with the self-shielded electrodes, protection from wind is similar to that of shielded metal arc welding, allowing it to be used for outdoor applications. Both gas shielded and self-shielded flux cored arc welding can be used in automated or robotic welding.

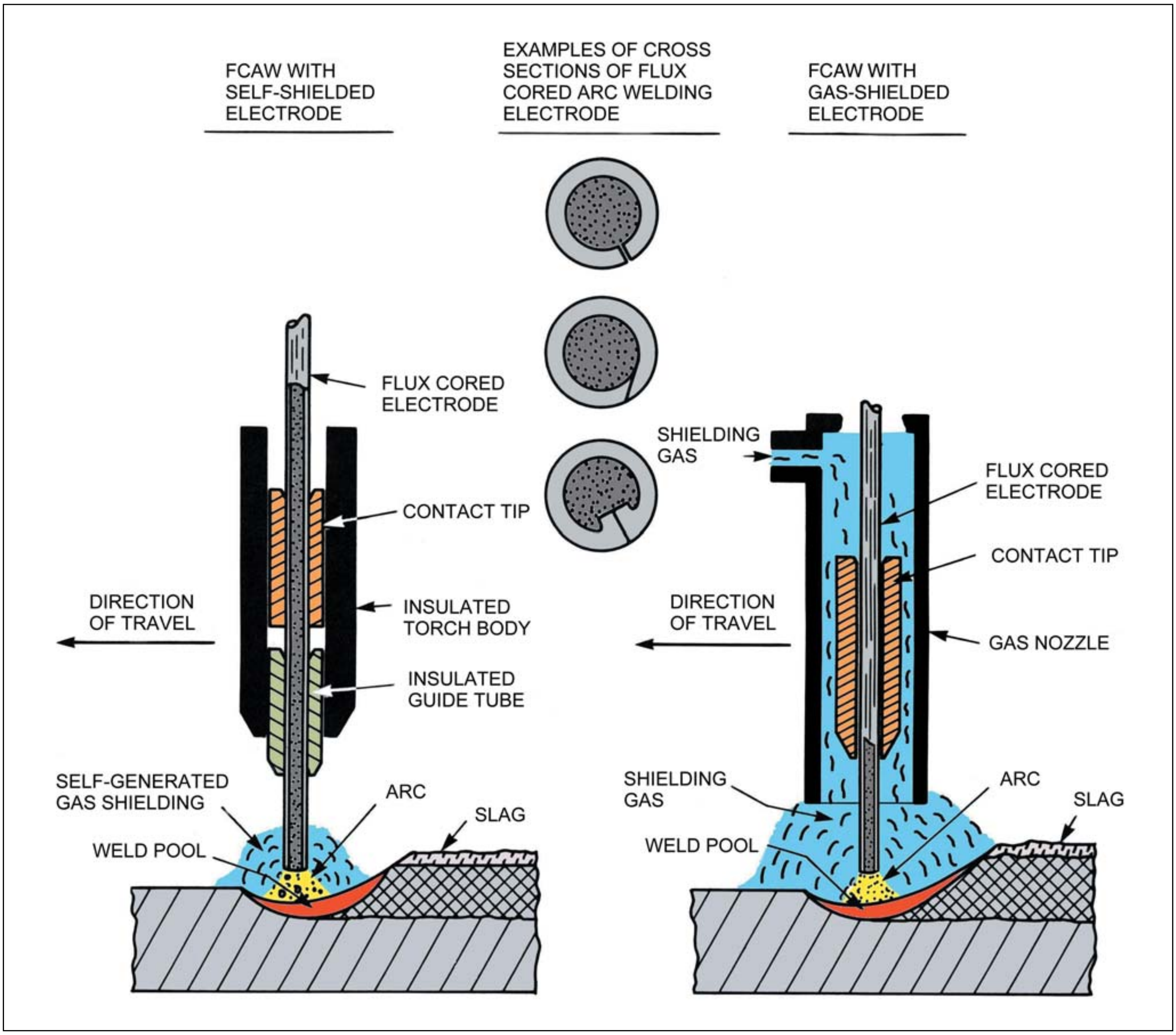
Flux cored arc welding has a wide range of applications. It is a versatile process utilized by fabrication shops for a variety of parts and products. It has the capacity to weld metals as thin as that used in vehicle bodies and as thick as heavy structural members of high-rise buildings.

Electrogas Welding

Electrogas welding (EGW), illustrated in Figure 1.13, is a mechanized arc welding process that utilizes either flux cored or solid electrodes. The shielding gas may be applied from an external source or produced by a flux cored electrode, or both. Electrogas welding has been used successfully on titanium and aluminum alloys in addition to steels. It is applied in the manufacture and repair of storage tanks, pressure vessels, ship hulls, and structural members.

The operation and applications of electrogas welding are similar to those used in electroslag welding, a high-energy-density process which is described in the section titled "Other Welding and Joining Processes." Although these processes utilize different heating methods, both are used to weld thick sections in the vertical position.

Electrogas welding machines vary in size from portable 75 lb (35 kg) units that are usually self-propelled to the more commonly used massive machines that are moved by cranes from one weld joint to another. Both the lightweight and heavy units are typically used to weld sections 1/2 in. to 3 in. (13 mm to 76 mm) thick using a single electrode. To maintain constant arc



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.17.

Figure 1.12—Schematic Representation of Flux Cored Arc Welding

voltage, the vertical movement of the welding head is usually automatic, though other methods can be implemented. For circumferential welds, the welding head is fixed while the workpiece is rotated with the axis in the horizontal position.

The welding current used in this process depends on the electrode diameter and type. In general, EGW machines operate at amperages as high as 400 A with solid electrodes and as high as 750 A with flux cored electrodes. Deposition rates for these machines are typically 15 pounds per hour (lb/hr) to 30 lb/hr (7 kilograms per hour [kg/hr] to 13 kg/hr). Travel speed along the joint is governed by section thickness and deposition rate.

Electrogas welding has the capacity to produce square-groove and single-V butt joints. This process is also used for welding T-joints. Simple edge preparation for these standard joints minimizes joint preparation costs. Weld soundness is generally excellent, and because transverse shrinkage is uniform, the joints are essentially free of angular distortion. In addition, the use of high current density results in high deposition rates. Thus, this process offers both economic and quality benefits.

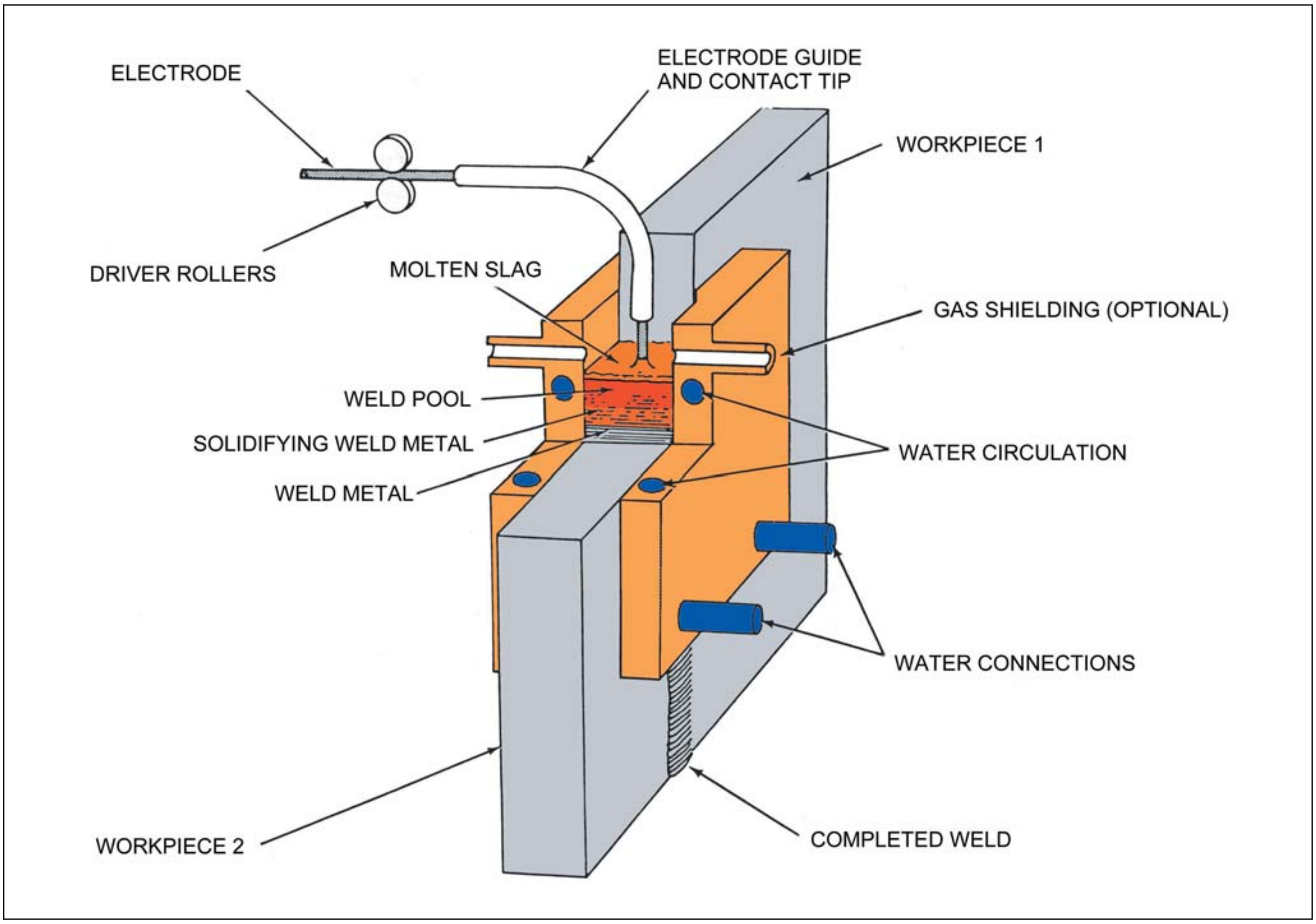


Figure 1.13—Schematic Representation of Electrogas Welding

Plasma Arc Welding

Plasma arc welding (PAW), illustrated in Figure 1.14, 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). Shielding from the atmosphere is provided by the ionized gas that emanates from the torch. This is supplemented by externally added shielding gas. No pressure is used to form welds in this process. Employed in the manufacturing, aerospace, and nuclear industries, 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 it to carry electric current. This constricted orifice concentrates the power, creating a high-power-density process. The PAW arc is stiffer and more stable than that used in gas tungsten arc welding. Thus, the PAW arc is less sensitive to the torch stand-off distance between the nozzle and joint.

As illustrated in Figure 1.14, in both the transferred arc and nontransferred arc process variations, the tungsten electrode is negative. In the transferred arc mode, the workpiece is positive, whereas in the nontransferred arc variation, the orifice nozzle is positive. The constricted orifice concentrates the heat to produce a plasma temperature more than three times that of an open arc process. Therefore, keyhole welding is possible in metal thicknesses up to 0.5 in. (13 mm) when implementing transferred arc plasma arc welding on a tightly fitted square butt joint. Thicker materials can be welded

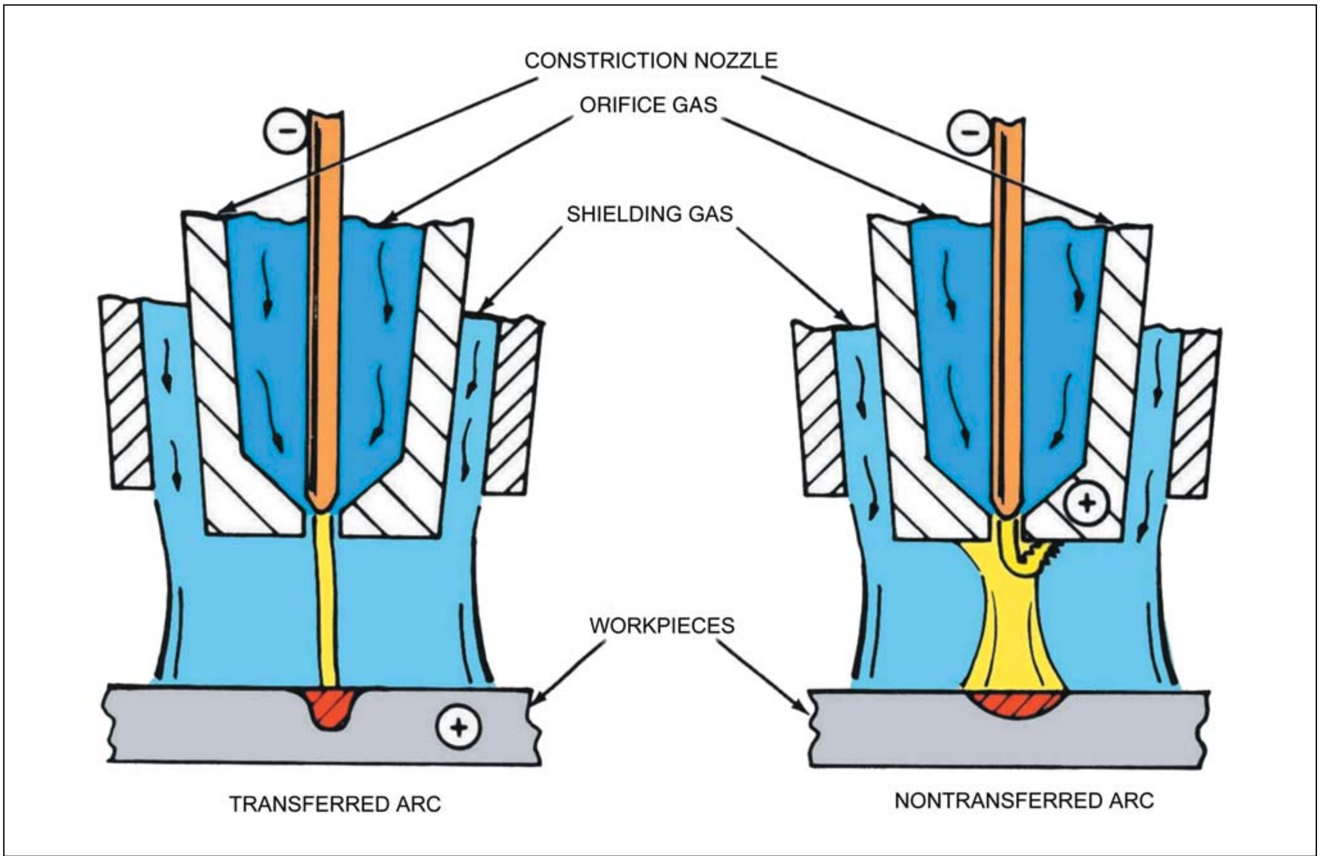


Figure 1.14—Schematic Illustration of Plasma Arc Welding: Transferred Arc (Left); Nontransferred Arc (Right)

using the keyhole method when combined with a V- or U-groove through a portion of the joint thickness.

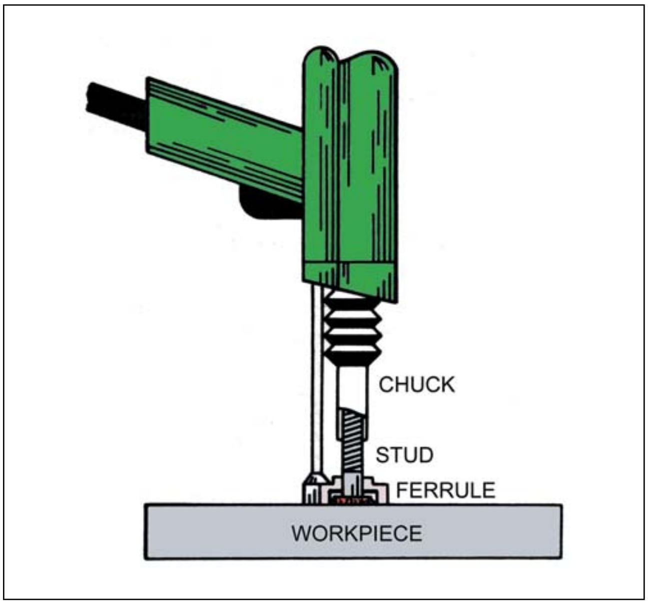
The keyhole technique results in excellent productivity. However, it demands precise travel speed and therefore requires mechanization. In contrast, nontransferred arc plasma welding is used mostly for melt-in welding techniques, surfacing, and thermal spraying applications. It lends itself to manual control in many instances.

A low-power version of plasma arc welding, sometimes referred to as *microplasma* or *needle arc welding*, is capable of welding materials as thin as 0.001 in. (0.02 mm). Much of this type of welding can easily be done manually.

Arc Stud Welding

Arc stud welding (SW), illustrated in Figure 1.15, is a versatile welding process used to join innumerable devices—usually fasteners—to base metal. This process utilizes an arc struck between a metal stud and the workpiece and is applied without filler metal and with or without shielding gas. Partial shielding may or may not be provided by a graphite or ceramic ferrule surrounding the stud. Pressure is applied when the faying (intimately fitting) surfaces are adequately heated.

In manual arc stud welding, the stud and the graphite or ceramic ferrule are loaded into the chuck and held against the workpiece at the desired location. When the gun trigger is depressed, the stud is lifted, drawing an arc that is sustained for the prescribed length of time set on the timer. For a stud 3/8 in. (9.5 mm) in diameter, a typical arc time is 1/3 second (s). Most studs require less than 1 second of arc time. A molten pool forms on the workpiece and on the end of the stud. Then, as the current stops flowing, the stud is plunged into the workpiece, and the two pools coalesce and solidify. This creates a weld across the whole cross section of the stud, plus some excess. The graphite or serrated ceramic ferrule serves as a spacer and a physical shield. It is recessed to shape the excess weld metal. Deoxidation is



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.63.

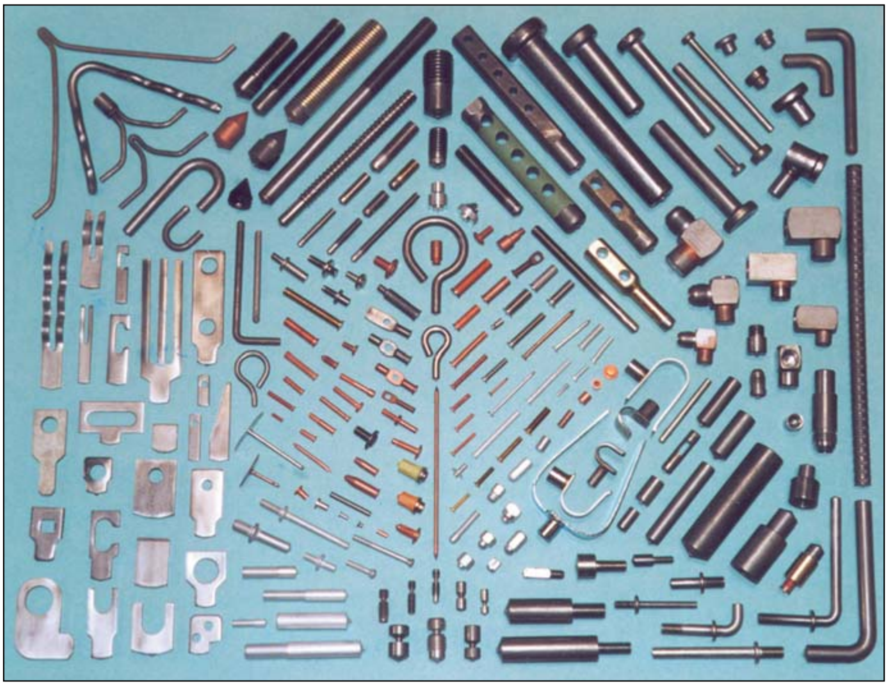
Figure 1.15—Schematic Representation of Stud Welding

accomplished with either an aluminum pellet or flux under a cap on the end of the stud. Once the parameters for a given application are set, little skill is required to implement the process. Figure 1.16 illustrates a variety of available studs.

Studs smaller than 1/4 in. (6 mm) in diameter typically use capacitor discharge energy. When small studs are used, the welding time is only a few milliseconds. A graphite or ceramic ferrule is not used due to the extremely short arc time. Moreover, shielding methods are not required unless the metal oxidizes extremely quickly, as does aluminum. In this case, inert gas shielding, usually argon, is required.

Power sources for arc stud welding are normally dc constant-current rectifiers or engine-driven machines with sufficient amperage capacity for the size of studs being welded. A bank of batteries may be used when sufficient electrical current is not available. Arc stud welding processes using dc constant-current rectifiers or engine-driven power sources are used extensively in automated systems.

The major advantages of stud welding are the minimal time and skill required for the operation. The process lends itself nicely to robotic welding. The process can be completely automated, or it can incorporate



Photograph courtesy of Nelson Stud Welding®

Figure 1.16—Variety of Studs Commonly Used in Stud Welding

automatic stud loading to the gun with manual gun manipulation. Alternatively, the studs can be loaded manually into the gun. A limitation of the process involves the use of a brittle base metal, such as gray cast iron, in which weld metal shrinkage cannot be tolerated and heat-affected zone cracking occurs.

RESISTANCE WELDING

Resistance welding (RW) encompasses a group of processes that effect the joining of faying surfaces with the heat obtained from the workpiece's resistance to the flow of welding current and with the application of pressure. Shielding gases are not needed because air is squeezed out of the faying surfaces by the force inherent to the processes. The vehicle manufacturing industry, among others, employs the resistance processes extensively in applications in which the product design specifies gauge thicknesses that are lapped. Access to both sides of the weld is also required for the electrodes to apply force. Fully automatic and robotic systems are used for many of these applications.

Commonly implemented resistance welding processes are resistance spot welding (RSW), resistance seam welding (RSEW), resistance projection welding (RPW), and resistance stud welding. The main process variables associated with these resistance welding processes are welding current, welding time, electrode force, electrode material, and tip configuration. Once the parameters for these variables are properly adjusted, very little skill is required to operate the equipment.

These four processes are used extensively in the joining of metals up to 3/16 in. (4.8 mm) thick that can be upset by the electrode force. In these processes, copper electrodes apply force to the lapped workpieces to be joined. The force on the faying surfaces at the joint interface squeezes out the air, and the base metal is rapidly heated. A short circuit practically exists when the high-current, low-voltage power is applied. However, most heating occurs at the location in the circuit where the electrical resistance is the greatest. It is essential that the metals to be joined have higher electrical resistance than the electrode. In other words, the electrical resistance must be greater between the two metals to be joined than between the electrode and base metal.

A great deal of resistance welding is performed with single-phase ac current. Unfortunately, the very high welding current on a single phase yields a poor power factor. Another resistance welding variation uses very high three-phase dc output current for short durations. This variation supplies an excellent power factor as the current load is balanced on all three phases. Yet another resistance welding approach utilizes the capacitor discharge method, which provides dc pulses as the capacitors discharge their store of electrical power. Although the total power requirement is relatively low in resistance welding, instantaneous power demand is very high. The electrical conductors must therefore be designed to carry the maximum kilovolt ampere (kVA) demand for the machine.

Good electrode tip shape and condition are important factors with respect to consistent weld quality. Thus, for production operations, schedules are normally established to provide for the cleaning and the remachining of electrode configurations to their original design.

Other important resistance processes include flash welding, upset welding, and high-frequency upset seam welding. Instead of welding lapped surfaces as in the previously described resistance welding processes, the flash, upset, and high-frequency upset seam processes weld together the edges of two workpieces or the edges of a rolled pipe seam. High-amperage alternating current and low voltage are normally used.

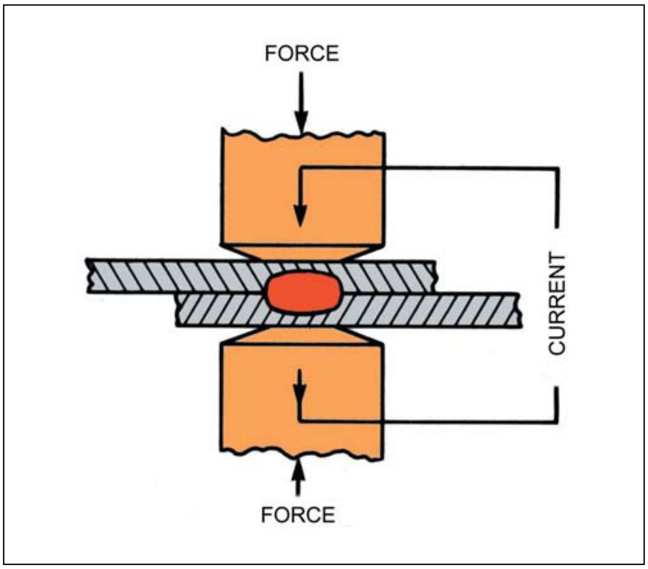
Spot Welding

Resistance spot welding (RSW) involves the application of the welding current through electrodes that concentrate the current and pressure in the area of the weld. A nugget of weld metal is produced at the location where the electrodes are positioned. Figure 1.17 illustrates this concept.

The electrodes used in spot welding not only conduct the welding current to the workpiece but also transmit a force and dissipate heat from the weld zone. Typically made of copper alloy, they have a straight shank and a conical or domed tip. It takes less than one second to make a single weld with industrial-duty equipment. For example, the joining of steel sheets 1/16 in. (1.6 mm) thick with the application of an alternating current of approximately 12,000 A and 4 V requires a weld time of 15 cycles or 0.25 s.

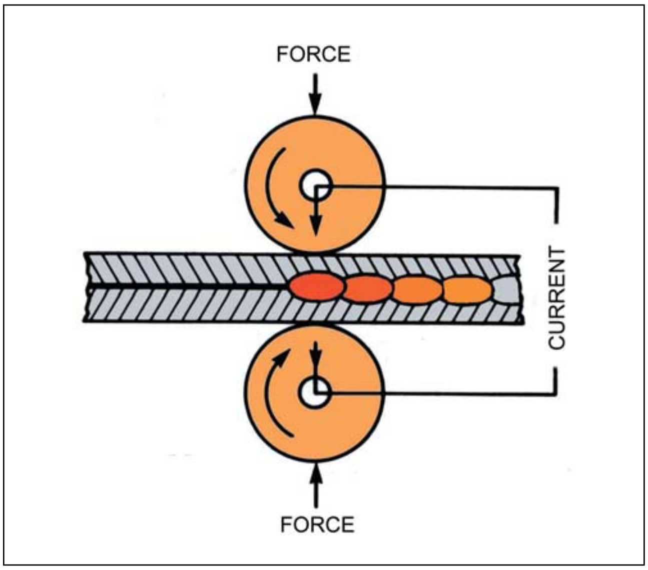
The basic equipment used in resistance spot welding consists of an electrical circuit, control equipment, and a system to apply force. This process is performed using a variety of equipment, ranging from utility spot welders to sophisticated systems that make hundreds of spot welds automatically within a few seconds.

Vehicle body panels require over 1000 spot welds using robotic systems to join them together in a few seconds. Sheet metal shops use less sophisticated systems to join many other thin-gauge products using spot welding. The minimal welding time and operator skill required are the main advantages of this process. The principal disadvantage is the need to have accessibility to both sides of the workpiece as opposed to being able to make welds from one side only.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(A).

Figure 1.17—Schematic Representation of Resistance Spot Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(B).

Figure 1.18—Schematic Illustration of Resistance Seam Welding

Seam Welding

Typically used to produce leak-tight joints in sheet assemblies such as automotive gasoline tanks, resistance seam welding (RSEW) utilizes the fundamentals of resistance welding to produce a seam along the length of the joint. The seam is created with copper wheel-type electrodes that make a continuous weld by generating overlapping spot welds, as shown in Figure 1.18, or one continuous weld (see below).

Because the overlapping of welds causes a shunting effect (that is, decreased electrical resistance due to weld overlap), the current and duty cycle required for resistance seam welding are somewhat higher than those used in resistance spot welding.

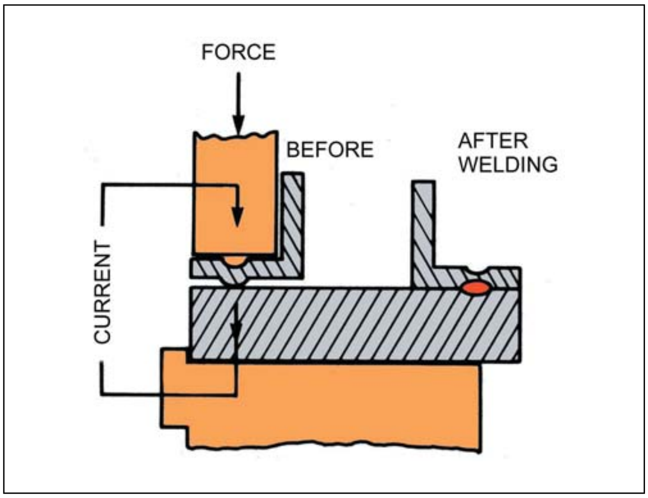
Resistance seam welding machines designed to weld at high speeds apply a continuous flow of current to the workpieces. This flow forms a continuously fused weld (as opposed to overlapping welds) between the lapped faying surfaces. Another type of resistance spot welding utilizes current interruptions that are long enough to form a series of separate spot welds. This type of operation is known as *roll spot welding*.

Projection Welding

Used primarily to join one stamped, forged, or machined part (e.g., a fastener such as a nut or a bolt) to another part (e.g., sheet metal), projection welding (RPW) is a resistance welding process that produces welds at predetermined points, indicated by projections made on the parts during their manufacture. The electrodes used in this process are similar to those described for resistance spot welding. The specially prepared electrode tips precisely locate the projections on workpieces to be joined. Figure 1.19 illustrates this concept, which is used to produce projection welds in various carbon and alloy steels and some nickel alloys.

In this process, one of the two workpieces to be joined is designed to have one or more protrusions or projections. These projections become weld nuggets when the welding current and electrode force are applied. When more than one projection is formed on the part, the height of every projection must be even to permit it to be in contact with the second member. This allows each joining member to be heated properly when the current and force are applied. When the thicknesses of the workpieces are unequal, the projection should be located on the thicker piece. This ensures that the heating of both members is balanced, which is conducive to the production of strong welds.

An advantage offered by resistance projection welding is its short weld time cycle, which leads to high productivity. The ability to produce numerous welds simultaneously with a single set of electrodes is highly desirable compared to processes that are limited to



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(D).

Figure 1.19—Schematic Representation of Resistance Projection Welding

producing one weld at a time. It is important to note, however, that precise control of all projection dimensions is imperative when multiple welds are made simultaneously. Another advantage offered by this process is that provisions are made to concentrate the heat at the weld locations by the projections themselves, which simplifies the backing side of the circuit.

Resistance Stud Welding. Resistance stud welding is a variation of the resistance projection process. Figure 1.20 illustrates threaded studs with the projections clearly visible. The dimensions of the projections must be controlled precisely, and equal pressure is required on all projections simultaneously. The pressure applied axially by the electrodes must be accurately aligned to produce welds of consistently high quality.

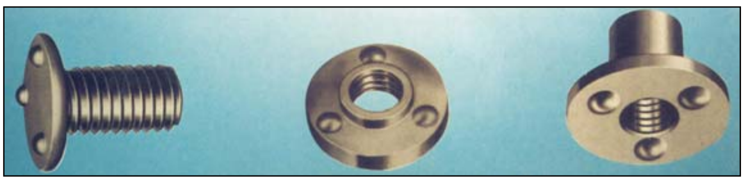
Studs for resistance stud welds are available in carbon steel and some alloy steels. The welding time is typically 10 cycles (0.17 second), fewer than that required for arc stud welding, which typically requires 20 cycles (0.33 second) for a 3/8 in. (10 mm) stud due to the extremely high currents used for resistance stud welding. However, the variety of studs is considerably more limited than that indicated for arc and capacitor-discharge stud welding (see Figure 1.16).

Flash Welding

Flash welding (FW), illustrated in Figure 1.21, utilizes both a flashing action (i.e., the rapid melting of the metal at the points of contact due to the high current density at the points) and the application of pressure to generate welds at the faying surfaces of butt joints. When the faying surfaces are heated to welding temperature, force is applied immediately to generate the weld. Molten metal is expelled, the hot metal is upset, and a flash is formed. Filler metal is not added during welding.

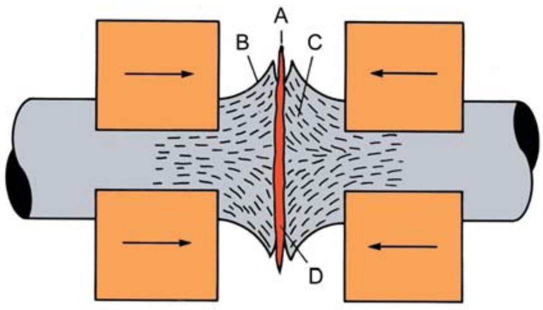
In this process, the workpieces are held firmly in copper-alloy jaws or clamps. Typically, one member is held stationary while the other is moved toward it. When contact is made, arc flashes occur between the edges. The applied force causes the molten metal to be expelled from the joint in a shower of sparks, and the metal close to the joint is deformed in a phenomenon known as *upset*. The irregularities and surface impurities are squeezed out into the upset portion, also termed *flash*, yielding a high-quality weld zone. This flash can be trimmed off for a smooth joint without stress raisers (i.e., changes in the section or surface that cause a concentration of stress, such as at the joint interface around the periphery of a spot weld).

Flash welding, usually an automated process, is widely implemented in the automotive, electrical, and petroleum industries. Applications range from the welding of a variety of material sections such as wires, rods, and shafts to the joining of rolled wheel rim ends.



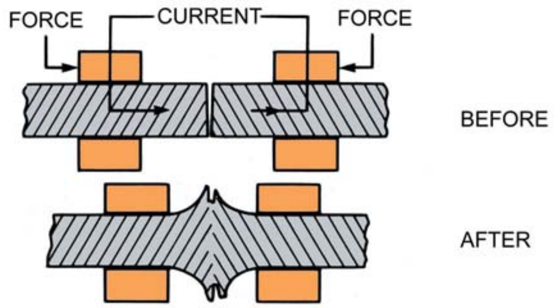
Photograph courtesy of the Ohio Nut & Bolt Company

Figure 1.20—Threaded Fasteners (Studs) Manufactured with Projections for Use in Resistance Stud Welding



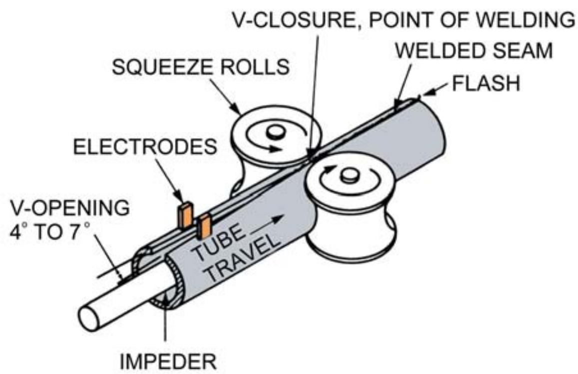
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.33.

Figure 1.21—Schematic Illustration of Flash Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(E).

Figure 1.22—Schematic Illustration of Upset Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.29.

Figure 1.23—Schematic Illustration of High-Frequency Upset Seam Welding

Upset Welding

Illustrated in Figure 1.22, upset welding (UW) produces welds by means of the resistance to the flow of the welding current through the area in which the surfaces are in contact and the application of pressure. Unlike flash welding, upset welding requires both workpieces to be held together and kept in contact under pressure before current is introduced. The completed weld zone is similar to that produced with flash welding. This process is used in wire mill applications and in the fabrication of products made of wire.

A process variation of upset welding, termed *electric resistance welding* (ERW), is used for the creation of longitudinal tubular seams. Although much of the welding current flows around the rolled section, the wheel-type electrodes are close enough to each other to produce sufficient current flow on the edges of the seam members for upset welding heat to develop. Squeeze rolls on either side of the tubular section force the edges together. This concept is similar to that used in high-frequency upset welding, except for the manner in which the welding current is introduced, as explained below.

High-Frequency Upset Welding

High-frequency upset seam welding (UW-HF), illustrated in Figure 1.23, is a process variation of electric resistance welding. Employed primarily in the joining of piping and tubular sections, this process involves the application of high-frequency current through the electrodes.

Initially, a metal strip goes through forming rolls to configure it into a pipe or tube. As the rolled section approaches the welding station, the V-opening of the edges is kept separated at an angle of 4° to 7° to the V-closure (the point of welding). This opening enables the maximum heating of the edges by the high-frequency current applied to the electrodes. The impeder also enhances the behavior of the current flow to achieve maximum edge heating. The squeeze rolls push the heated edges together to produce the welded seam. The excess metal that has been squeezed out creates flash, which is subsequently trimmed off to create a smooth surface at the welded area.

Sliding electrodes are preferred over the wheel-type electrodes since only light pressure is needed for this high-frequency, high-current application. When the frequency is increased from 60 hertz (Hz) to 400 kilohertz (kHz), the heating effect is not as deep but is more concentrated, thus resulting in increased welding speeds and increased productivity. Less electrical power is required when using high-frequency current due to concentrating the heat where needed rather than spreading it out. However, high-frequency current can cause hazards as it broadcasts electrical noise that can affect the performance of sensitive electronic equipment that may be in the area.

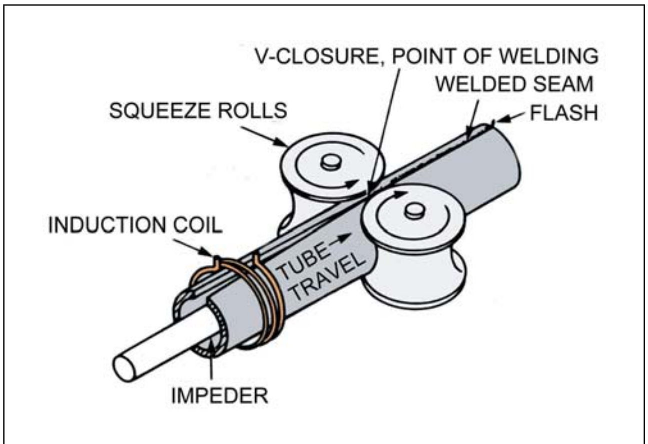
Figure 1.24 illustrates the use of an induction coil for the high-frequency upset welding of butt joints for pipe seams. When using an induction coil, heating is accomplished by inducing high-frequency current using a copper coil that encircles the pipe or tube. The induction coil heating method is preferred when a problem is posed by the electrode's contacting the surface of the pipe or tube.

SOLID-STATE WELDING

The solid-state welding (SSW) processes accomplish joining by the application of pressure at a temperature below the melting point of the base and filler metals. Certain solid-state processes weld at approximately room temperature.

The solid-state processes have the capability to join dissimilar metals that cannot be successfully joined with processes involving molten metal. For example, the welding of aluminum to steel is readily accomplished by several solid-state processes inasmuch as the two materials are not melted and mixed. When iron and aluminum are melted and mixed together, a brittle intermetallic compound results; however, if iron and aluminum are joined with no melting involved, an interatomic attraction develops, producing a section with no brittle intermetallics.

The six solid-state processes discussed here are presented in descending order from the highest-temperature process to the lowest-temperature process. These are forge welding (FOW), friction welding (FRW), diffusion welding (DFW), ultrasonic welding (USW), explosion welding (EXW), and cold welding (CW).



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, Figure 6.31.

Figure 1.24—Schematic Illustration of Induction High-Frequency Upset Seam Welding

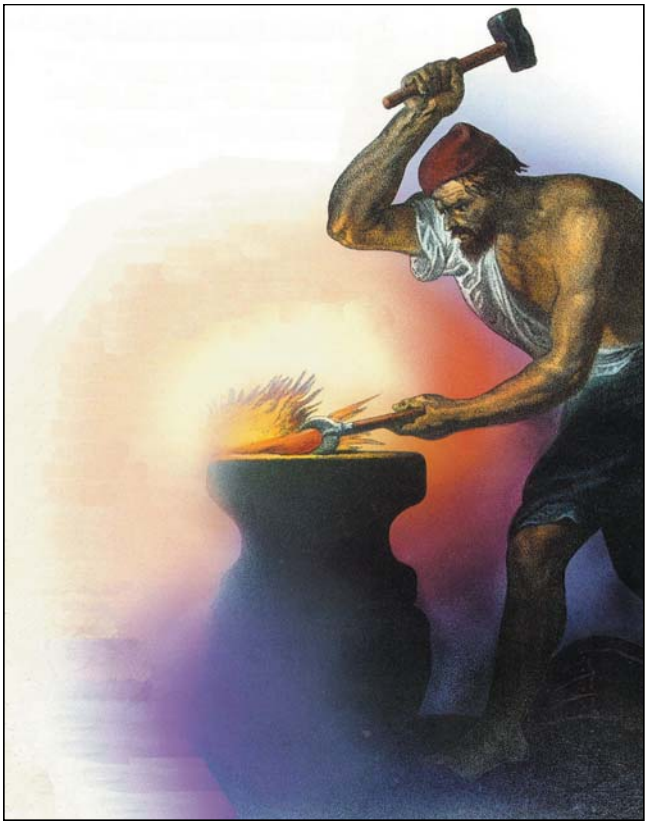
Forge Welding

Forge welding (FOW) accomplishes joining by heating the materials to welding temperature and then applying pressure (hammer blows or steady pressure) to effect the weld. Possibly dating back to circa 4000 B.C., forge welding is the oldest known welding process. Even then, articles were forged from both ferrous and nonferrous metals. It is postulated that forge welding may have been accomplished by first heating the articles with the aid of a bellows to a high enough temperature for forging. As illustrated in Figure 1.25, hammer blows were applied to weld and shape the heated portion of the metal.

Forge welding remained the only welding method until late in the nineteenth century, when the electric and oxyacetylene processes came into existence. At present, some materials are still forge welded using the hammer method, while others are joined using the die and the roll welding (ROW) methods. In the fabrication of laminated coins, for example, three layers of metal are roll welded together before the stamping operation is initiated. Another contemporary application of this process involves the welding of low-carbon steels in the production of tubing and clad metals.

Friction Welding

Friction welding (FRW), illustrated sequentially in Figure 1.26, is a solid-state process that accomplishes joining with the heat produced by means of the compressive force generated by the workpieces' rotating or moving in relation to each other, causing the displacement of material from the faying surfaces. Friction



Source: ESAB, 1990, *Connections*, ESAB Welding and Cutting Products, Hanover: Pennsylvania, p. 2.

Figure 1.25—Ancient Forge Welding

welding machines are therefore designed to convert mechanical energy into heat at the joint to be welded. Normally, one of the two workpieces is circular or nearly circular in cross section. Shielding gas, flux, and filler metal need not be used. This process successfully joins a wide range of similar materials as well as a number of dissimilar metals, including aluminum to steel. The oil, defense, aerospace, automotive, electrical, medical, agricultural, and marine industries all employ friction welding.

To perform friction welding, a machine rotates one of the workpieces and forces it against the other, which is held stationary. This step is depicted in Figure 1.26(A). As shown in Figure 1.26(B), frictional heat at the joint interface raises the metal to forging temperature. Axial pressure forces the hot metal out of the joint, as can be seen in Figure 1.26(C). Oxides and other surface impurities are removed from the soft, hot metal.

Friction welding machines are equipped with (1) a drive head as a means for applying axial force and (2) a yoke or platform for mounting the tooling, which holds the workpiece to be welded in a fixed position as it is being welded. Machines range in size from those capable of welding a 0.5 in. (13 mm) diameter steel bar to those that can weld a steel bar 5.0 in. (125 mm) in diameter. The friction welding cycle is usually automatic. If automatic loading and unloading devices are installed, the machines are completely automatic. As a result, little skill in terms of manual dexterity is needed.

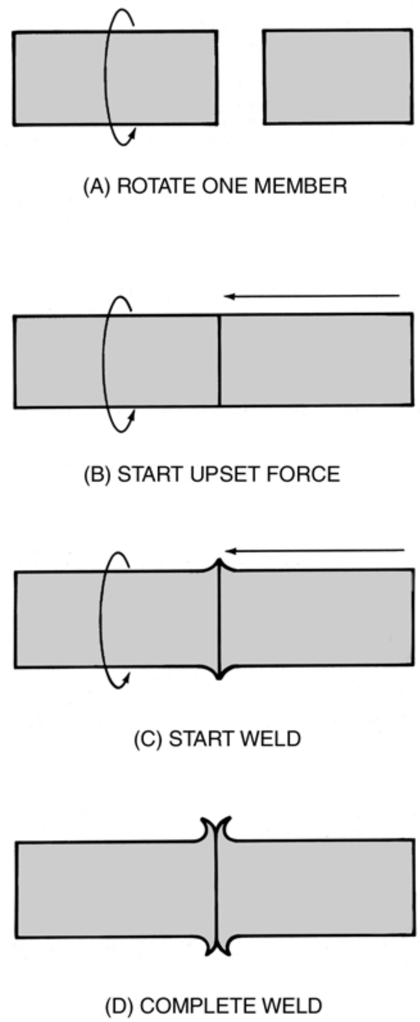


Figure 1.26—Schematic Illustration of Friction Welding

However, a mechanical aptitude and an understanding of machine operation are required to set up jobs properly and maintain equipment in good operating condition.

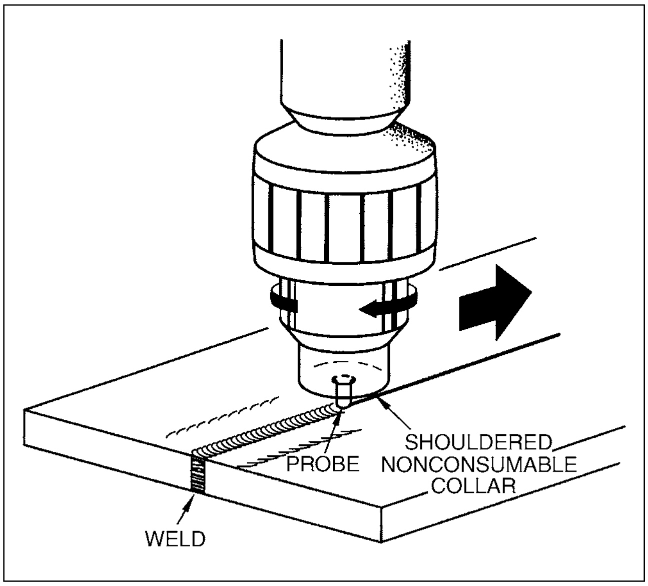
Two major process variations of friction welding are commonly employed. In the first, termed *direct drive friction welding,* the moving workpiece is held in a motor-driven collet and rotated at a constant speed while axial force is applied to the stationary workpiece. The stationary part must be held rigidly to resist the axial force and prevent it from rotating. Rotation is continued until the entire joint is heated sufficiently. Then, simultaneously, the rotation is stopped and an upsetting force is applied to complete the weld. In this case, the welding process variables are rotational speed, axial force, welding time, and upset force. Since energy must be provided at the rate necessary to make the weld, the process requires a relatively high-powered drive motor.

The second variation is known as *inertia friction welding*. In this method, energy is stored in a flywheel, which is accelerated to the required speed by a drive motor. The flywheel is coupled directly to the drive motor by a clutch. The flywheel is also coupled to the collet, which grips the rotating workpiece. A weld is made by applying an axial force through the rotating workpiece while the flywheel decelerates, transforming its kinetic energy to heat at the joint. The weld is completed when the flywheel stops. The welding variables for this process are the flywheel moment of inertia, flywheel rotational speed, axial force, and upset force (if used).

The time required to generate friction welds is measured in seconds. Inertia welds require from less than 0.5 seconds to approximately 15 seconds, exclusive of the time needed to accelerate the flywheel to the designated speed. With either type of machine, the time required to load and unload parts is longer than the actual weld time.

Friction Stir Welding. A more recently developed process variation of friction resistance welding is friction stir welding. This process was specifically designed for use with certain aluminum alloys. Figure 1.27 illustrates the basics of the process, wherein a probe or tap with a diameter of 0.20 in. to 0.24 in. (5 mm to 6 mm) is rotated between the square-groove faying edges. The shouldered nonconsumable collar has a smoothing effect on the top surface. A temperature of 840°F to 900°F (450°C to 500°C) is generated as the slightly tilted rotating probe travels along the length of the joint, stirring the hot metal, thereby creating the weld. A typical welding speed is 24 in./min (600 mm/min) on an aluminum section thickness of 0.25 in. (6 mm).

Aluminum thicknesses ranging from 0.06 in. to 0.5 in. (1.5 mm to 30 mm) can be welded by friction



Courtesy of the Edison Welding Institute

Figure 1.27—Schematic of Friction Stir Welding

stir welding using a conventional milling machine equipped with the welding tool rather than a milling machine cutter. High quality welds with no porosity or cracks result. These welds pass bend and tension tests, which evaluate fracture in the heat-affected zone.

The advantage offered by friction stir welding as compared to friction welding is that the workpieces need not be rotated against each other while being held under pressure. A disadvantage is that the choice of metals that can be joined by means of friction stir welding is very limited, as indicated above.

Friction Stud Welding. Friction stud welding is a solid-state welding process in which the stud is rotated at several hundred to several thousand revolutions per minute while held under pressure against the surface of the workpiece. At the required temperature, the rotation is quickly stopped, and the pressure on the stud is increased to produce the weld.

The greatest potential of this type of stud welding is derived from the absence of molten metal in the process. This allows for increased flexibility in the joining of dissimilar metals. Some combinations form brittle intermetallic compounds when melted and mixed, as is the case with aluminum and steel. However, if the weld is effected by bringing the atoms into close enough proximity to form a bond while in the solid state, these intermetallics are avoided, and satisfactory joint properties are achieved. On the other hand, the biggest disadvantage of friction stud welding is its lower productivity compared to the other stud welding processes (see above).

Diffusion Welding

Diffusion welding (DFW) is a solid-state process that achieves coalescence by applying pressure at high temperatures with no relative motion or visible deformation of the workpieces. A filler metal may be inserted between the faying surfaces.

Figure 1.28 depicts the stages that result in the joining of two workpieces during diffusion welding. Figure 1.28(A) indicates the asperities (peaks and valleys) of an equiaxed grain structure at the edges of the two workpieces approaching each other with only the peaks touching. Figure 1.28(B) represents the first stage, in which pressure and heat application cause deformation of the grains at the interface of the workpieces, with the boundaries at the interface still defined. Figure 1.28(C) illustrates the second stage, in which diffusion across the boundaries occurs as atoms migrate to new positions and pores from the valleys are eliminated. Figure 1.28(D) depicts the third stage, in which the heat and pressure have continued to the extent that volume diffusion of the atoms has occurred and caused the boundaries to disappear. A new grain formation is evident across the interface, virtually eliminating the pores.

Diffusion welding occurs in the solid state when properly prepared surfaces are in contact under predetermined conditions of time, pressure, and elevated temperature. The applied pressure is set above the level needed to ensure essentially uniform surface contact but below the level that would cause macroscopic (visual) deformation. The temperature is generally well below the melting point. A filler metal, which is typically positioned before welding as an insert or plating, may be used. In general, the filler metal lowers the temperature, pressure, or time required for welding, thereby permitting welding in a more economical atmosphere.

The heating required for diffusion welding can be generated in a furnace or retort or by means of resistance techniques. Pressure is applied by uniaxial fixturing; by dead-weight loading; or by utilizing a press, differential gas pressure, or differential thermal expansion of the workpieces. When joining assemblies with intersecting planar surfaces, high-pressure autoclaves or differential gas pressure techniques can be used. Uniaxial methods of applying pressure are limited to welding parallel planar surfaces roughly perpendicular to the

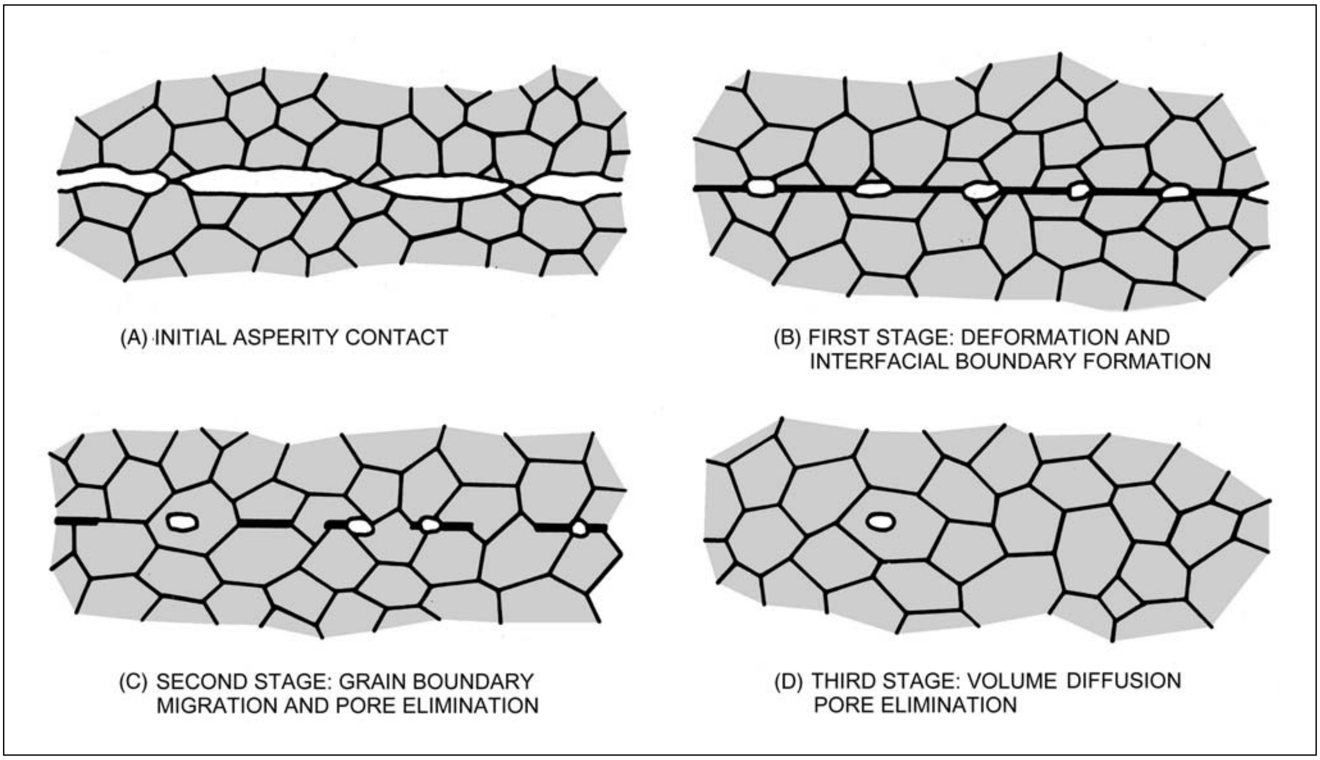


Figure 1.28—Schematic Representation of the Stages of Diffusion Welding

direction of load. These techniques, which are mechanized, require the appropriate equipment. The encapsulating or "canning" of workpieces in an evacuated envelope to be welded is necessary when differential pressure techniques are applied. The encapsulating of parts is also useful in the implementation of other diffusion welding process variations.

A variety of similar and dissimilar materials can be joined by diffusion welding. Nonetheless, the process has a number of limitations. Equipment costs are high. This process is economical only when close dimensional tolerances, expensive materials, or special material properties are involved. For this reason, diffusion welding is widely used mainly by the aerospace, nuclear, and electronics industries. Although it is sometimes used to fabricate complex, one-of-a-kind devices, it is better suited to moderate production volumes. Diffusion welding is not adaptable to a high production rate. Moreover, the costs incurred in the use of consumables are high if precious filler metals or inert gases are used. A high level of operator training is required for most operations. Only fully automated operations permit the use of semiskilled personnel.

Ultrasonic Welding

Ultrasonic welding (USW), used in the semiconductor, microcircuit, electrical, aluminum fabricating and chemical industries, is a solid-state process that forms a weld by applying localized high-frequency vibratory energy while the workpieces are held together under light pressure. A sound metallurgical bond is produced without significant heat.

The basic equipment required in this process is shown in Figure 1.29. A light clamping force applies pressure through the reed to the sonotrode tip. The transducer is wedge-shaped where it attaches to the reed. It produces the vibration that disrupts surface roughness and impurities prior to welding. The workpieces are placed beneath the sonotrode tip and supported underneath to sustain the force used, thereby holding the workpieces together.

Though ultrasonic welding bears a resemblance to resistance welding, it utilizes no electrical current flow or significant heat across the joint interface. The transducer used in the process typically vibrates at 20 kHz. The vibratory energy disrupts surface roughness and impurities, interatomic attraction occurs, and a weld results. The equipment components must be acoustically tuned to each other or the weld will not take place. It should be noted, however, that the ultrasonic welding process is limited to the size and capability of the transducer.

Process variations have been developed to form welds in spot, ring, line, and seam configurations. Metals such as aluminum and copper and nonmetals such as thermoplastics are routinely joined by ultrasonic welding. The process has the capacity to weld thin sections to thick sections and join a variety of dissimilar materials. For metals, the process is limited to the welding of relatively thin, lapped sections and the joining of wires to sheet or wires to other wires. Once the parameters are set, little skill is required to operate the ultrasonic welding process. This process can be used for automatic and robotic applications.

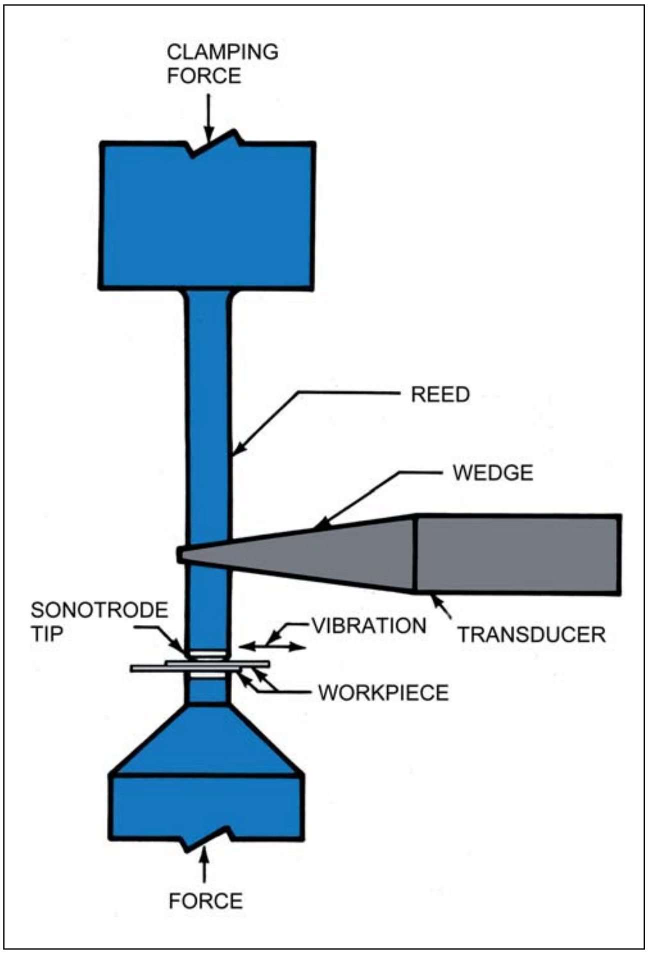


Figure 1.29—Schematic Representation of Ultrasonic Welding

Explosion Welding

Explosion welding (EXW) is a solid-state process that utilizes a controlled detonation to impact two workpieces at a very high velocity, thereby creating a weld. Explosion welding occurs essentially at ambient temperature. As illustrated in Figure 1.30, the explosion

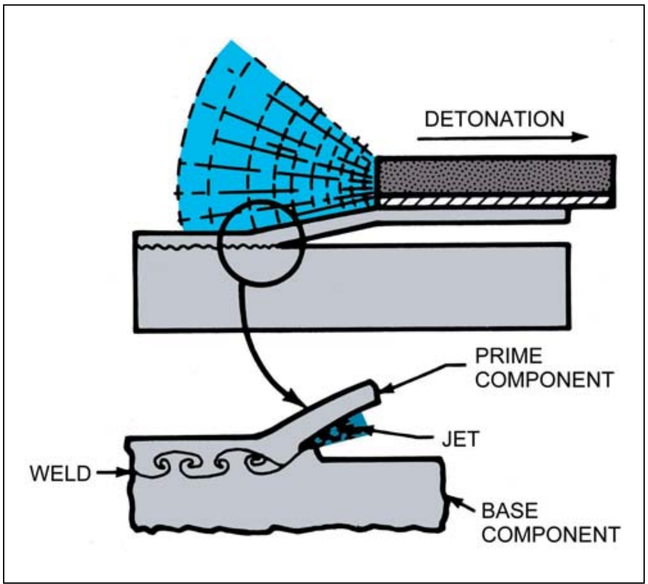


Figure 1.30—Schematic of Explosion Welding

accelerates the prime component toward the base component at a speed that causes the formation of a metallic bond between them when they collide. The explosion bends the prime component locally as the detonation quickly progresses. Then, the prime component quickly crosses the standoff distance and impacts the base component. Any heat that may be produced by the impact is not significant to the joining process, as welding is accomplished by the plastic flow of the metal pieces across the faying surfaces.

Explosion welding can be used to join metals having sufficient strength and ductility to withstand deformation at the high velocities required to implement the process. It is typically used to join thin metals to dissimilar thicker metals. For example, explosion welding is commonly implemented to join thin-gauge stainless steel (the prime component) to thick mild steel (the base component) to create a corrosion-resistant surface on a massive object. In this case, the base component may be supported by a backing if it is not large enough to sustain the impact of explosion welding on its own.

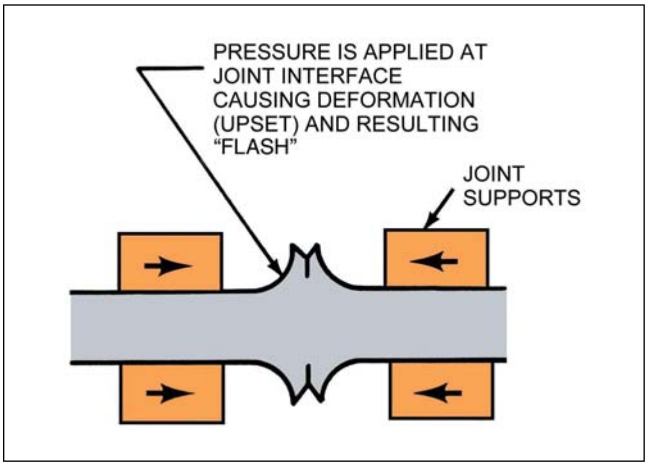
Cold Welding

Cold welding (CW) is a solid-state process that involves the use of pressure at ambient temperature to effect a weld with substantial deformation of the workpiece. Though this process resembles upset welding, no electrical current flows across the joint. No heat is used or generated; force alone is employed to accomplish joining. As shown in Figure 1.31, the metal must be supported near the joint. A force strong enough to cause upset is then applied. This forces out surface roughness and impurities and promotes interatomic attraction by moving the atoms at the edge of the workpieces closer together, thereby creating a weld.

Not all metals can be joined using the cold welding process. Successful cold welding requires that at least one of the metals being joined be highly ductile and exhibit minimal work hardening. Metals that work-harden quickly when deformed start cracking before joining is accomplished. Metals that have a face-centered cubic arrangement of atoms and do not work harden quickly are best suited to the process. These include aluminum and copper as well as gold, silver, and platinum. Thus, cold welding is used in the manufacture of wire made of these metals.

OXYFUEL GAS WELDING

Oxyfuel gas welding (OFW) encompasses a group of processes that utilize the heat produced by a gas flame to melt the filler metal, if used, and the base metal, thereby creating a weld. Filler metal and the application of pressure may or may not be used. Oxyfuel gas welding is used mainly in circumstances in which faster processes are not available. One notable exception is the repair welding of gray cast iron. For this application, a cast iron filler rod is used with the oxyfuel gas flame to produce repaired areas that are very similar in composition and properties to the casting itself. If a color difference in the repaired area is acceptable, an alternate



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 2.2.

Figure 1.31—Schematic of Cold Welding

procedure may be used. This involves the use of a brass filler rod to produce a braze weld, which accomplishes the repair without melting any of the cast iron.

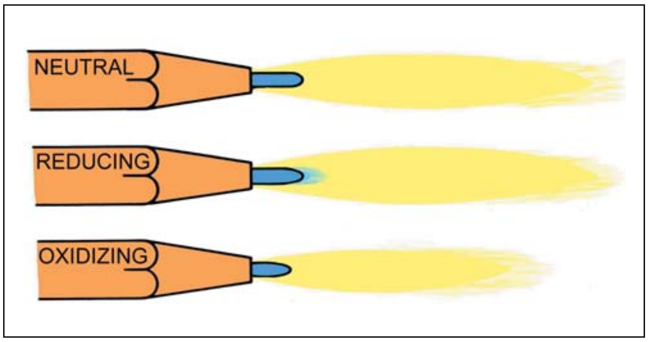
In the oxyfuel gas welding process, a combustible fuel gas is mixed with oxygen and ignited. The temperature at which it burns is a function of the amount of oxygen present in the gas mixture. If fuel gas with no oxygen added were ignited, aided only by the 20% oxygen contained in ambient atmosphere, the flame temperature would be too low for welding. If the gas were mixed with nearly 100% oxygen, flames would reach temperatures exceeding 5500°F (3038°C).

The fuel gas most commonly used is acetylene. Compared with other fuel gases, acetylene can produce the hottest and most concentrated flame. The oxyacetylene flame also produces carbon dioxide, which serves as a shielding gas. Other fuel gases such as stabilized methylacetylene-propadiene (MPS) and hydrogen are sometimes used to weld metals with low melting temperatures.

Figure 1.32 demonstrates three types of flames that can be produced with oxyacetylene mixtures. In the illustration at the top, the flame is neutral, containing approximately equal volumes of oxygen and acetylene. The inner cone and outer bush are the only parts of the flame. The flame is considered neutral because it neither significantly adds to nor subtracts any elements from the weld pool.

It can be noted that the flame illustrated in the middle, known as a *reducing flame*, has a secondary feather extending from the inner cone. This secondary feather is caused by excess acetylene in the flame mixture, which alters the chemical composition of the weld pool by reducing iron oxide (reducing effect) and adding carbon (carburizing effect).

In the bottom flame, oxygen is predominant in the gas mixture and has an oxidizing effect on the weld pool. Referred to as an *oxidizing flame*, this flame has a harmful effect on the properties of ferrous alloys. Like the neutral flame, the oxidizing flame has just two parts. However, it is usually shorter than the neutral or reducing flame and has a sharper point than the neutral flame.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.58.

Figure 1.32—Types of Oxyacetylene Flames

The rate of heat input is slower in oxyfuel gas welding than in any other process that uses heat to bring the base metal to the melting temperature. This slow rate of heat input results in increased weld production time, increased energy consumption, and wider heat-affected zones with the attendant coarse-grain structure and poor mechanical properties, especially in high-strength ferrous alloys. When welding metals with excellent heat conduction, such as copper-based alloys, preheat is required to lower the temperature gradient sufficiently to enable the oxyfuel flame to form the weld.

A variation of oxyfuel gas welding known as *pressure gas welding* (PGW) uses the flames to bring the abutting edges to the melting temperature and then applies pressure to force the two workpieces together. This process variation has been mostly replaced by flash welding (FW), which has the capacity to produce welds at a much faster speed.

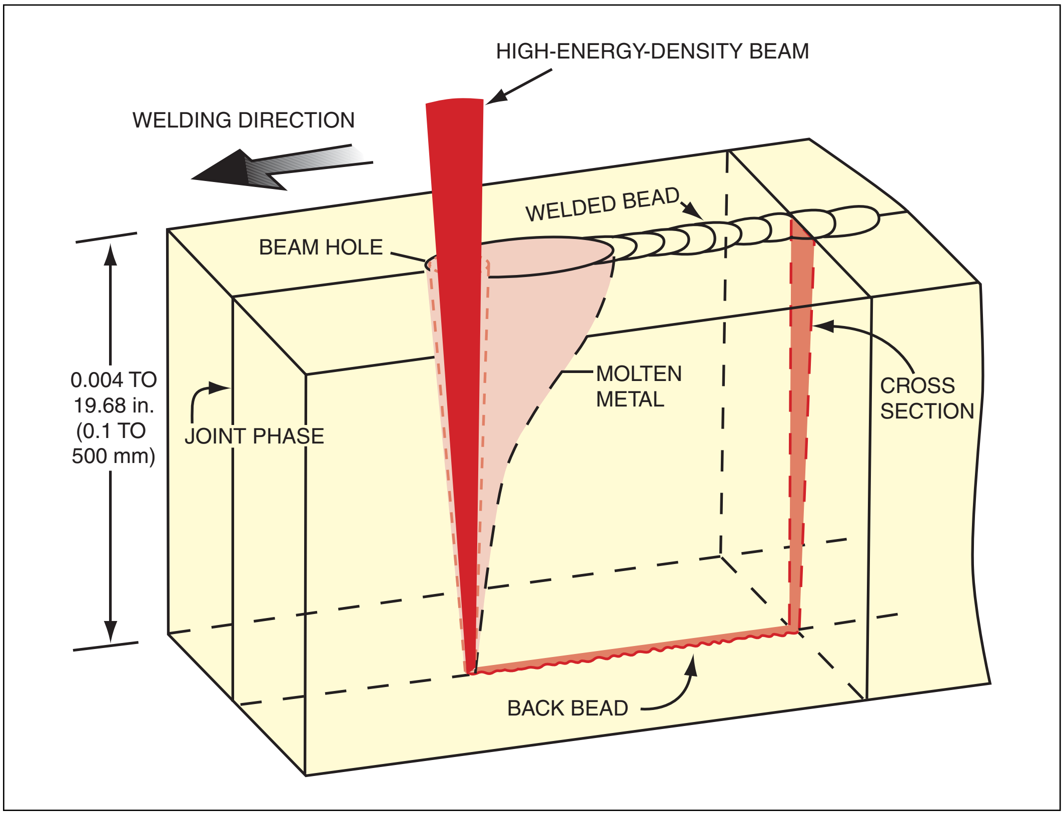
Oxyfuel gas welding equipment is relatively inexpensive and widely available. As it can also be used for cutting, brazing, soldering, surfacing, and heating applications, it is also extremely versatile. Thus, the oxyfuel gas process is well suited for small businesses and individual consumers.

OTHER WELDING AND JOINING PROCESSES

Four important welding and joining processes are discussed in this section. These are electron beam welding, laser beam welding, electroslag welding, and adhesive bonding.

Electron beam and laser beam welding are referred to as *high-power-density processes*. They utilize a very high rate of heat input. These processes usually require automation and have excellent potential for high-speed production. The high-power-density processes are capable of producing welds in which a vaporized hole that fully penetrates the metal thickness is surrounded by molten metal. This type of weld, termed a *keyhole weld*, is illustrated in Figure 1.33. As the keyhole reaches the bottom surface, either the process (the welding gun) or the joint is moved at a speed that allows the molten metal surrounding the vaporized hole to flow around to the rear, coalesce, and solidify, forming the weld. Plasma arc welding (see above) is related to these processes in that it also uses the keyhole technique with the high energy density produced by means of a constricted arc plasma.

The most common joint design used in the high-power-density processes is a precisely fitted square-groove



Source: Adapted from Powers, D. E., and G. R. LaFlamme, 1988, EBW vs. LBW—A Comparative Look at the Cost and Performance Traits of Both Processes, *Welding Journal* 67(3): 25–31, Figure 1.

Figure 1.33—Schematic Representation of a Keyhole Weld

butt joint for an autogenous weld. These processes may also use consumables. Filler metal can be either shim stock or wire. Shim stock is placed between abutting edges, or wire is fed into the joint.

The heat-affected zones in keyhole welding with these processes are normally very narrow and accompanied by rapid cooling rates, which are advantageous with some alloys. However, if slower cooling rates are desired, the joint area to be welded must be preheated.

Electroslag welding, like electrogas welding (described under the section titled "Arc Welding") is used to join thick sections in the vertical position, usually in a single pass. Both of these processes are significantly more cost effective than multipass procedures with conventional arc processes.

Adhesive bonding is similar to brazing and soldering in some respects. Like brazing and soldering, some adhesive bonding techniques utilize heat. Heat may be applied during the process or generated by the curing of the adhesive. As is the case with brazing and soldering, adhesive bonding involves no melting of the surfaces being joined. Unlike in brazing and soldering, however, no metallurgical bond is formed.

Electron Beam Welding

Used for high-precision and high-production applications involving most metals, electron beam welding (EBW) accomplishes joining by means of a concentrated stream of high-velocity electrons that is formed into a beam to provide a source of intense local heating. The basic equipment required for most electron beam welding includes a vacuum chamber, controls, an electron beam gun, a three-phase power supply, an optical viewing system or tracking device, and work-handling equipment. The operation of this equipment may be either semiautomatic or automatic.

Electron beam welding is illustrated schematically in Figure 1.34. Electrons are dispersed from the electrically excited, negatively charged cathode. The grid (bias cup) partially shapes the electron beam. The speed of the electrons is greatly accelerated to 30% to 70% the

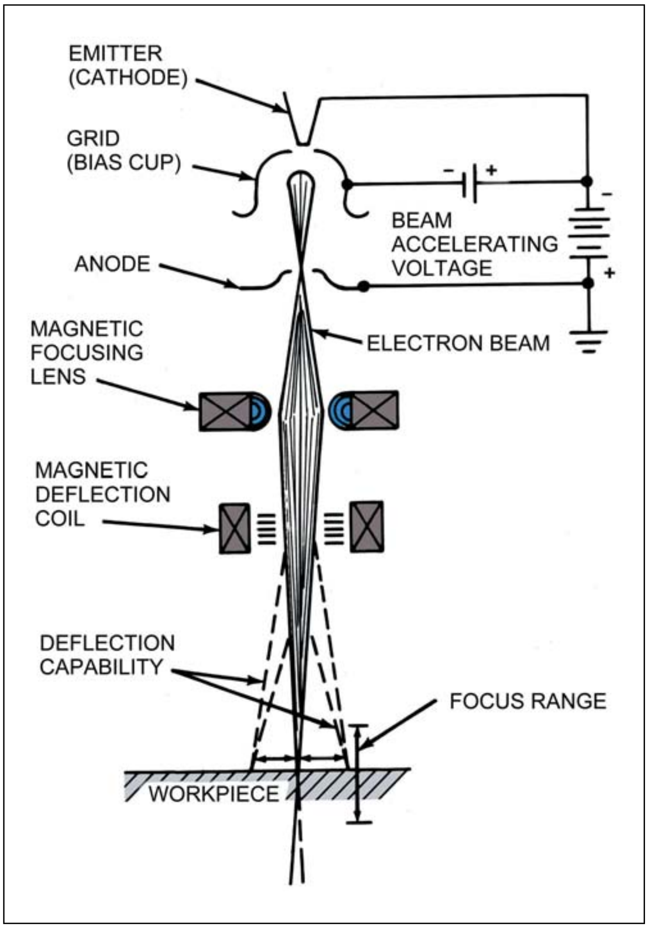


Figure 1.34—Schematic Representation of Electron Beam Welding

speed of light, and the beam is shaped by the positively charged anode. The diffused beam then passes through the magnetic focusing coil, which focuses it on the weld site. The beam subsequently passes through the magnetic deflection coil, which has deflection capabilities, if these are desired for the application.

The electron welding beam process can focus the beam onto a minute spot approximately 0.04 in. (1 mm) in diameter. As the metal is bombarded by the electrons, the rapid heating produces a vapor hole surrounded by the molten metal that forms the weld. The molten metal flows to the rear of the vaporized hole and coalesces as the workpiece or beam is moved along the joint. The vacuum, if one is used, provides very effective shielding from the atmosphere. Even a moderate vacuum provides better protection from oxidation than inert gas shielding from a nozzle. Precise control of travel along the joint is required for full weld penetration. Moreover, because the electron beam can be so small, edge preparation and fitup must be precise. Sufficient shrinkage to cause weld buildup on the surface may occur in thick sections, even without filler metal.

The three process variations of electron beam welding—high vacuum, medium vacuum, and nonvacuum welding—are based on the degree of vacuum used. As shown in Figure 1.34, the high vacuum (EBW-HV) variation, which often is referred to as *hard-vacuum electron beam welding*, typically utilizes a pressure of 1×10^{-3} torr (1.3×10^{-2} pascal [Pa]). The medium vacuum variation (EBW-MV) typically employs a vacuum of 2×10^{-1} torr (26.7 Pa). The nonvacuum variation (EBW-NV), often referred to as *atmospheric electron beam welding,* obviously uses no vacuum at all, which is 760 torr (1×10^5 Pa).

Figure 1.35 illustrates the different levels of penetration produced by these process variations. It can be observed that the high vacuum process renders the greatest penetration. With the medium vacuum process, the weld profile is wider and not as deep. The weld profile becomes even wider and shallower with the nonvacuum process.

Several other variables affect joint penetration in high vacuum electron beam welding. These include travel speed, beam power, beam focal point, and beam focus or shape. For instance, when welding thin sections, the intensity of the beam can be lowered by changing the shape of the beam into a straight line, a circle, or another configuration.

A major advantage of high vacuum electron beam welding is that it produces deep, narrow welds with low total heat input and comparatively narrow heat-affected zones. The high vacuum process produces the greatest penetration, with a weld depth-to-width ratio of about 25:1. The narrow heat-affected zone produced is illustrated in Figure 1.36. In addition, very high travel speeds are possible on thin sections. If the speed is too fast, however, joint penetration may be less than 100%, and porosity may occur near the weld depth termination. If the travel speed is too slow, the molten metal around the keyhole fails to coalesce, and no joining takes place. It is also important to note that when welding thick sections of some alloys, magnetic fields cause the beam to curve away from the joint. In this case, the weld will not fully penetrate, and the lower portion of the joint will not be welded.

Electron beam welding has its limitations, however. First, the capital costs associated with this process are substantially higher than those incurred with arc welding equipment, though unit cost is competitive when production volume is high. When performing electron beam welding in a moderate vacuum or no vacuum, atmospheric molecules quickly dissipate the beam energy. This phenomenon may make electron beam

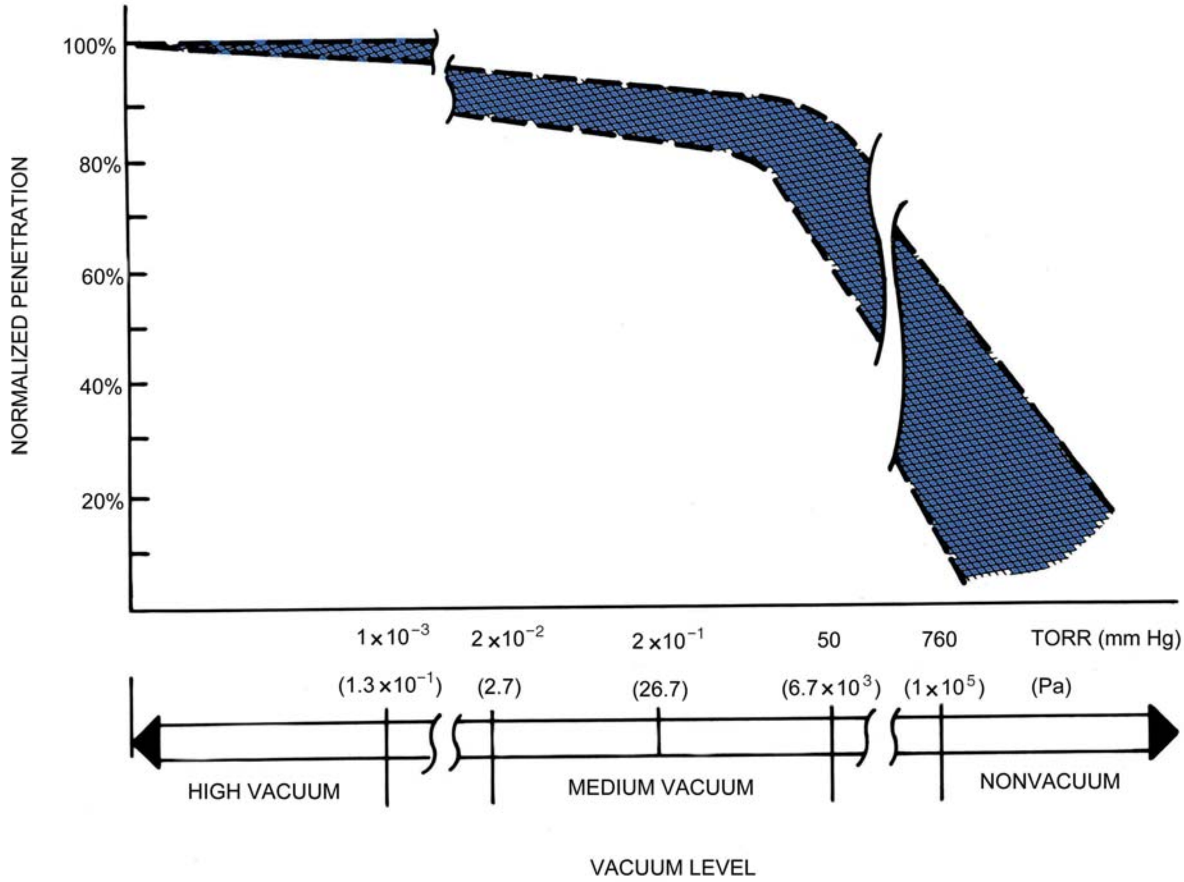


Figure 1.35—Electron Beam Penetration as a Function of Operating Pressure

welding less desirable than other processes with considerably smaller capital investments.

In addition, in the high vacuum and medium vacuum variations, a significant amount of pump-down time is incurred while placing the parts in a vacuum chamber, though welding in a medium vacuum involves less pump-down time than the high vacuum process. As they require a vacuum chamber, the high and medium vacuum processes are limited with respect to the size of parts that can be welded. Production speed can be augmented by increasing the size of the vacuum chambers to permit them to accommodate more workpieces. Another option to increase productivity is the use of chambers in a circular, or carousel, arrangement. After the workpiece is loaded into the carousel, it is sent at timed intervals through the chambers, where the vacuum becomes progressively higher. In the final chamber, the desired vacuum is attained, and the workpiece is welded.

When performing electron beam welding in a vacuum, porosity and spatter can be caused by the evolution of gas as the metal is melted by the beam, a phenomenon known as *outgassing*. When the evolving gas causes the ejection of molten drops of metal that scatter over the work surface, the solidified drops take the form of spatter. It is important to keep the workpiece clean in order to minimize outgassing. In the presence of a vacuum, the gases and impurities present in the material evolve during welding, causing the workpiece and the chamber to become coated with residue.

In nonvacuum electron beam welding, the vacuum is used only to create the electron beam. Therefore, the weldment size is not limited to the size of a vacuum

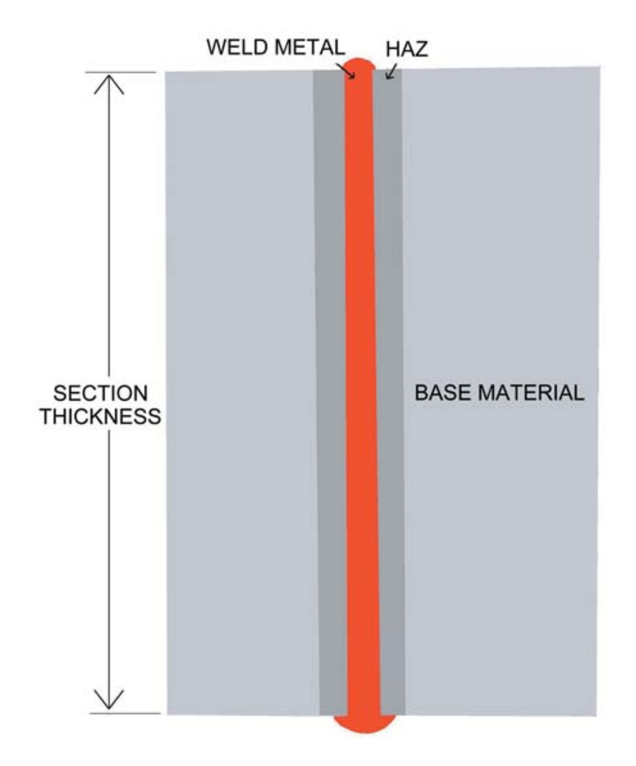


Figure 1.36—Deep, Narrow Weld Produced by Electron Beam Welding

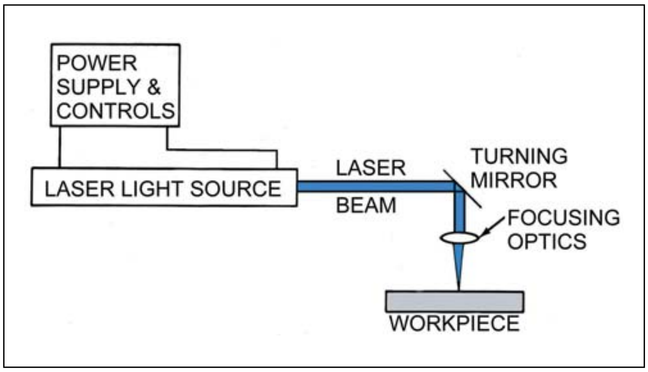


Figure 1.37—Schematic Illustration of Laser Beam Welding

chamber. However, penetration capability is much lower, and shielding gas is required. In addition, as a vacuum chamber fails to provide protection from the X-radiation emitted by the beam, more contamination occurs. Thus, operators must control the process remotely from outside the required radiation enclosure. Personnel must be protected from the ozone and other noxious gases produced during the nonvacuum process.

Laser Beam Welding

Used extensively in the automotive industry, laser beam welding (LBW) effects the fusion welding of materials with the heat supplied by a laser beam that impinges on the joint. The laser beam is generated from a concentrated beam of coherent, monochromatic light in the infrared or ultraviolet frequency portion of the electromagnetic radiation spectrum. Therefore, the beam is invisible.

As illustrated in Figure 1.37, the beam is directed by mirrors and focused on the workpiece with reflective focusing optics devices or lenses. The minimally divergent raw beam is focused into a small spot, after which it diverges rapidly. Consequently, the proper distance between the lens and the focal point of the lens is crucial to obtaining the greatest power density on the base metal.

When comparing power input to power output, laser beam welding is actually rather inefficient. Only 8% to 15% of the electrical power input results in output of photons, depending on the type of laser being used. The remainder of the power is consumed in the heating of the laser equipment. For this reason, laser beam welding fails to achieve the same penetration capabilities as electron beam welding.

Nevertheless, several lasers have good penetration characteristics. For example, the carbon dioxide gas laser, with rated outputs as high as 25 kilowatts (kW), can produce keyhole welds in steel more than 1 in. (25 mm) thick in one pass. A two-pass weld made from both sides also increases penetration capability. Though the yttrium aluminum garnet (YAG) solid-state lasers have power ratings below those recorded by their carbon dioxide counterparts, the YAG lasers are significant in welding, piercing (see the section titled “Laser Cutting” below), and heating applications.

Laser beam welding can be performed with inert gas shielding. Alternatively, the beam can pass through glass and weld in an evacuated area. Unlike in the electron beam welding process, atmosphere does not impede the travel of the laser beam, and the process does not produce X-radiation. In addition, the beam can be directed by special mirrors to more than one workstation.

Extreme caution must be taken in the high-voltage area of the cabinet where laser equipment is housed. When work is being performed on the high-voltage section of the laser equipment, the manufacturer's instructions and warnings should be carefully heeded. Operators must be careful to avoid scattered radiation in the vicinity of the beam's impingement. A safety enclosure is mandatory for protection against scattered radiation. The appropriate protective eyewear and clothing for the given type of laser must be used.[10]

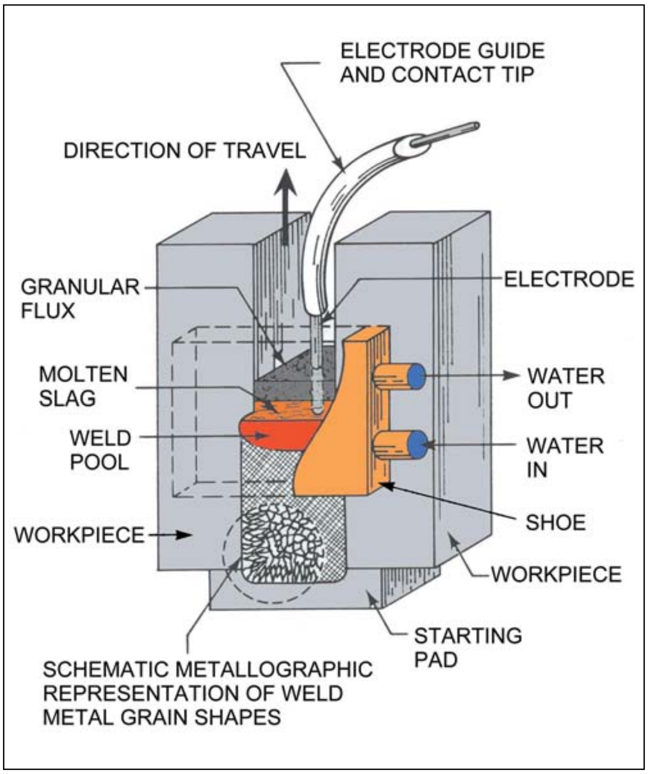
Laser equipment is highly sophisticated and expensive, requiring knowledgeable personnel to install it, set parameters, and maintain the equipment. However, laser equipment does not often require highly skilled operators.

Electroslag Welding

Electroslag welding (ESW) effects the joining of metals with molten slag that melts the filler metal and the surfaces of the workpieces. This process uses neither shielding gas nor the application of pressure. Illustrated in Figure 1.38, electroslag welding is not an arc welding process. Initially, the process has an arc, but once the molten pool of metal and slag rise high enough to quench the arc, the process continues as an electric resistance process. An electrically conductive molten bath of slag, heated by means of resistance to the welding current, provides the energy for melting and fusing the base and filler metals. The slag floating on top of the molten weld pool shields the pool from the atmosphere and melts the filler metal and joint faces.

Although electroslag welding is similar to electrogas welding, these processes differ in their heating methods. Electroslag welding (ESW) effects joining with the heat generated by passing electrical current from the electrode to the workpiece through molten slag, whereas in electrogas welding, an arc is maintained to provide heating. In both of these processes, once the weld is initiated, welding must not cease until the weld is completed inasmuch as restarting after a mid-length stop produces large discontinuities. Because the weld travel speed is only approximately 1/2 in./min to 1-1/2 in./min (0.2 mm/s to 0.6 mm/s), the weld metal and wide heat-affected zone exhibit a coarse grain structure with relatively low notch toughness. With their high heat input to the base metal, neither of these processes can be used on applications and alloys that do not tolerate coarse grain structures.

As can be observed in Figure 1.38, electroslag welding utilizes a nonconsumable tube to guide the electrode into the molten slag bath. Conventional electroslag equipment ranges from portable machines weighing about 75 lb (35 kg) to more massive units requiring cranes for transport from one location to another. The lightweight units may be self-propelled while welding. The heavier units, which are generally supported on a vertical column, move on tracks or screws while welding.



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.51.

Figure 1.38—Schematic Representation of Electroslag Welding

The welding process can incorporate single or multiple electrodes. Electrode oscillation may be implemented to join sections from approximately 1/2 in. to 20 in. (13 mm to 500 mm) thick. The edges of two sections are joined in a single pass, with the weld progressing in a vertical direction. The molten slag and weld metal are contained in the joint by copper shoes or dams that may be water cooled. If a section thickness exceeds the capability of electroslag welding with a single electrode, multiple electrodes may be employed.

The welding current utilized in this process varies appreciably depending on the number of electrodes used and the joint thickness. Several thousand amperes are required to weld thick sections with multiple electrodes. Deposition rates for single electrode machines are typically 15 pounds per hour (lb/hr) to 30 lb/hr (7 kilograms per hour (kg/hr) to 13 kg/hr. This rate is multiplied by the number of electrodes used.

10. For further information on safe practices, see American National Standards Institute (ANSI), *American National Standard for Safe Use of Lasers*, ANSI Z136.1, Orlando, Florida: Laser Institute of America (LIA).

A variation of the electroslag welding process is the consumable guide method, described below. The basic equipment required for both electroslag welding and consumable guide electroslag welding is the same except for the design of a guide tube and the requirements for vertical travel. The basic equipment includes a power source, an electrode guide tube, a wire feeder, a welding head, and retaining shoes or dams. An oscillator may or may not be required.

Consumable Guide Electroslag Welding. Consumable guide electroslag welding (ESW-CG), illustrated in Figure 1.39, is a process variation that utilizes a consumable guide tube. The guide tube must be as long as the length of the joint to be welded. The electrode feeds through the consumable guide tube, and the tube becomes shorter as it is consumed by the rising pool. The metal from which the consumable guide tube is made must be compatible with the metal being welded since it becomes part of the weld metal. The tube is secured at the top of the joint and extends to within about 1 in. (25 mm) of the bottom of the joint length. Removable shoes or dams that can be fixed into place are used to retain the molten weld metal and slag.

A continuous wire electrode is fed through the tube, and an arc is struck. The molten metal and slag subsequently form a pool. As the slag pool rises, the end of the guide continuously melts and contributes to the weld metal. The system remains in equilibrium as long as the slag pool exists in sufficient depth. Loose flux can be added if the weld flashes, indicating arcing. Donut-shaped insulators are spaced every 4 in. to 6 in. (100 mm to 150 mm) to prevent the short circuiting of the consumable guide tube to the joint base metal. An alternative to the spaced insulators is the use of guide tubes with a flux coating. This coating serves as insulation and supplies flux in small quantities as the guide tube end is progressively melted.

The applications of consumable guide electroslag welding are similar to those used in conventional electroslag welding. However, the length of the joint to be welded is limited to the length of the consumable guide tube. The advantage of this process is that its setup and operation are simple, requiring less sophisticated equipment.

Adhesive Bonding

Adhesive bonding (AB) is a joining process in which nonmetallic adhesive material is placed between the faying surfaces of the pieces to be joined, referred to as the *adherends*, followed by a curing procedure to complete the bond. The bonding agent placed between the adherends consists of an adhesive in the form of a liquid, paste, or tacky solid. Although natural organic and inorganic adhesives are available, synthetic organic polymers are usually employed to join metal assemblies. The adhesive undergoes certain physical or chemical property changes, which produce a bonded joint with the desired properties.

For the surfaces of the adherends to wet properly, their surface-free energy must be greater than that of the adhesive. This is usually the case for metallic and polymeric adhesives. However, contaminants on the metal can lower the surface-free energy and prevent the formation of a good adhesive bond. Therefore, contaminants must be removed by washing the surfaces with a solvent before bonding. Other removal techniques include grinding, grit blasting, and the use of abrasive paper and pads.

An adhesive must have low viscosity during the bond-forming process in order to spread evenly over the surface of the adherend. If the viscosity is too high, the adhesive will not completely wet the surface and will entrap gases or liquids in the bond line. To minimize this tendency, pressure is applied during curing.

Adhesive bonding offers many advantages. The skills required to implement the process are usually minimal. This joining process has the capacity to join metal to nonmetallic materials such as plastics and creates no heat-affected zone. In addition, adhesives have low processing temperatures, good stress distribution, and excellent vibration and sound dampening. Providing a smooth surface appearance, they not only bond the adherends but also act as a sealant or coating to protect against chemicals and moisture. The process produces no depressions from localized electrode pressure such as those that may occur in welded joints, and it can float out minor irregularities in the faying surfaces of the adherends.

Figure 1.40 presents a photograph of an adhesive bond used to join the thin aluminum skin of a satellite dish to the "Z" support members, maintaining the precise dish shape without any irregularities.

Limitations of the adhesive bonding process include low peel strength, curing time for the joints to develop full strength, and an operational temperature ceiling of 600°F (316°C). Adhesives may also degrade rapidly when highly stressed in a hot, humid environment.

Weld Bonding. Weld bonding, a variation of adhesive bonding, involves the augmentation of an adhesively bonded joint by means of resistance spot welds. This procedure combines the benefits of the fusion made by the spot welds with those of the adhesive bond. This combination of processes distributes stress from applied loads more evenly than spot welding alone. A leak-tight joint is produced.

Figure 1.41 illustrates weld bonding. It shows an outside corner of a small tank that has been formed and lapped with the end pieces. Excess adhesive is visible

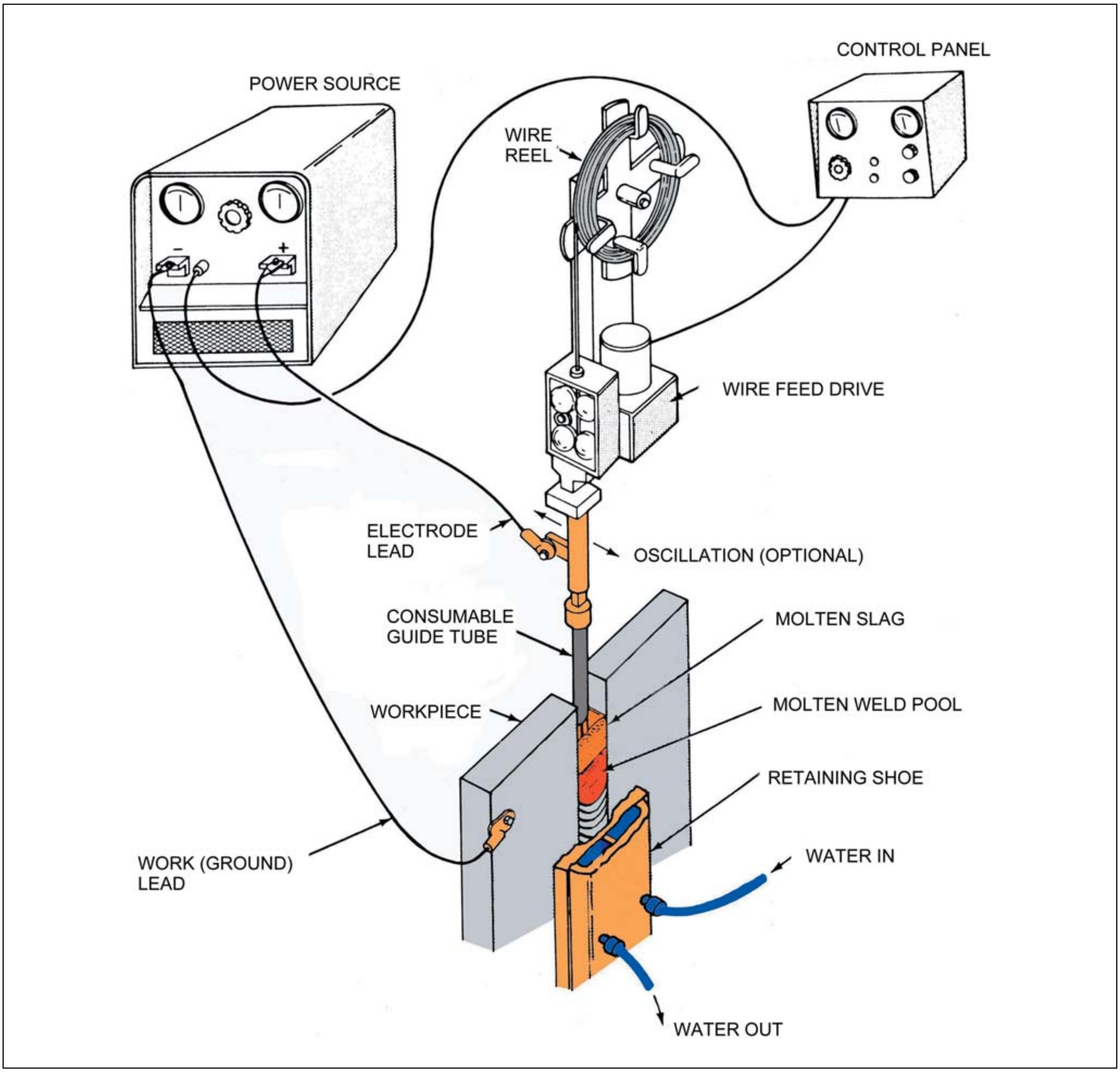
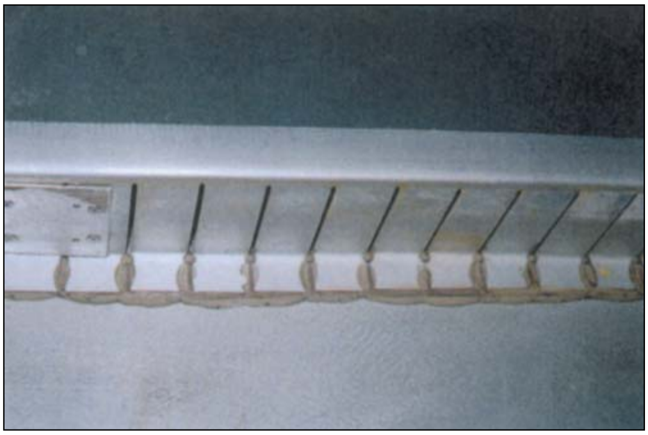


Figure 1.39—Schematic Representation of Consumable Guide Electroslag Welding

along the seams, and two depressions made by resistance spot welding are clearly visible on the long edge.

BRAZING AND SOLDERING

Brazing (B) and soldering (S) share a number of features. Both are liquid-solid state processes as they involve molten filler metal and solid base metal, which do not melt or mix. In both brazing and soldering, metallurgical bonds are produced by mutual diffusion rather than by fusion. Predominantly, the molten filler alloy diffuses into the base metal. Some base metal is also dissolved, diffusing into the filler metal. Although the fundamentals of bonding are the same for both processes, the temperature required to effect joining

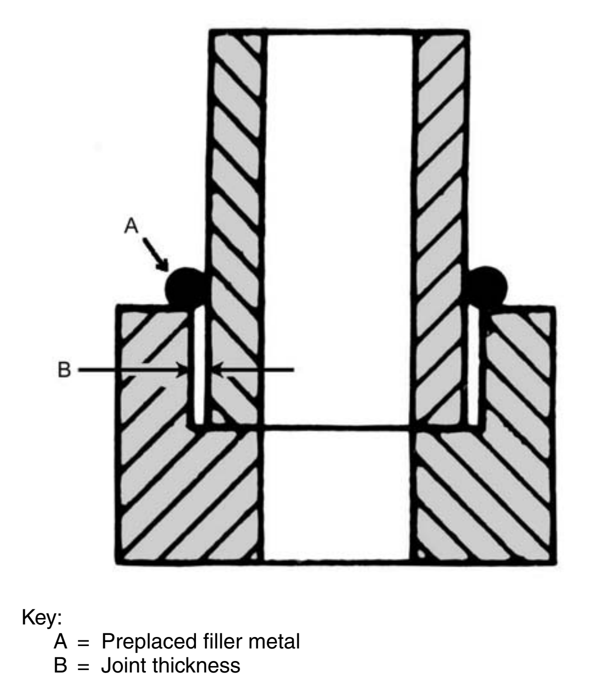


Photograph courtesy of Vertex Communications

Figure 1.40—Adhesive Bonding on a Satellite Antenna

Photograph courtesy of LeTourneau University

Figure 1.41—Weld Bonding of a Small Tank



Source: American Welding Society (AWS) Committee on Brazing and Soldering, 1991, *Brazing Handbook*, Miami: American Welding Society, Figure 12.24A.

Figure 1.42—Typical Joint for Brazing and Soldering

determines whether the diffusion process is considered brazing or soldering. Brazing takes place when the metal is heated to above 840°F (450°C), while soldering occurs below this temperature.

Both brazing and soldering are implemented with joints designed for capillary action, as illustrated in Figure 1.42. A filler metal with low viscosity is drawn into a small space (capillary)—typically 0.003 in. (0.1 mm) wide—between faying surfaces. The drawing power of the capillary action is greater than gravitational force, so filler metal can be drawn into the joint even in the overhead position.

For these processes to form successful bonds, the faying surfaces of the workpieces must be metallurgically clean. If not, discontinuities will develop, and bonding will not occur. The metal must be cleaned so that its microstructure is exposed. Only when the microstructure of the metal is exposed can diffusion take place. Thus, brazing or soldering operations typically begin with mechanical cleaning followed by an application of flux, which chemically reacts with impurities, rendering the surface metallurgically clean. The flux also protects the cleaned surface through the heating cycle of the brazing or soldering operation.

The machining of parts for brazing and soldering must be precise enough to maintain the required fitting tolerance for proper joint thickness for several reasons. First, joint strength decreases as the joint thickness (the distance between the two workpieces) increases. Second, for the sake of economics and good capillary action, the joint thickness should be less than 0.010 in. (0.3 mm). In addition, some brazing and soldering alloys are costly and should not be used needlessly. Smaller joint thickness requires a smaller amount of a brazing or soldering alloy.

The applications of brazing and soldering are broad. Brazing is used for expensive and critical components such as jet engine parts as well as for comparatively inexpensive applications such as bicycle frames. Soldering is important in the plumbing industry for the joining of copper tubes and fittings and in the electrical field for the joining of wires and printed circuit connections.

Brazing

The brazing processes achieve a bond between materials by heating them in the presence of a filler metal that has a liquidus above 840°F (450°C) and below the solidus of the base metal. The brazing filler alloys must be molten at temperatures above 840°F (450°C) to join the base metals, which are completely solid at the brazing temperature. The filler metal flows between the closely fitting joint surfaces by means of capillary action.

The different brazing processes are referred to according to the method used to apply the heat. The most widely used processes are torch (TB), furnace (FB), induction (IB), resistance (RB), dip (DB), infrared (IRB), and diffusion brazing (DFB).

Torch Brazing. Torch brazing (TB), illustrated in Figure 1.43, is accomplished by heating the parts to be brazed with one or more oxyfuel gas torches using various fuels. Manual torch brazing is normally performed using hand-held torches. Automated torch brazing machines use preplaced fluxes and preplaced filler metal in paste, wire, or shim form.

Figure 1.43—Torch Brazing

Manual and mechanized torch brazing processes are used to make lap joints in relatively thin sections ranging from 0.01 in. to 0.25 in. (0.25 mm to 6 mm). The joints can be brazed rapidly, but brazing speed decreases as the material thickness increases.

Furnace Brazing. Furnace brazing (FB) involves the use of a furnace to heat fluxed or cleaned parts with the filler metal placed at the joints. This process can be performed in continuous or batch mode. Furnace selection depends on the rate of production and the size of the assembly to be processed. Continuous furnaces are most effective for high production rates and simple joint designs. Batch furnaces with protective atmospheres are commonly used to fabricate relatively small groups of brazements. They are also used to supply the special heating and cooling cycles required for distortion control or heat treatment. Both the batch and continuous furnaces are easy to operate. In many cases, the operator need only load, unload, or apply the filler metal.

Furnace brazing is particularly suited to the fabrication of brazements of complex design. For example, the critical application of a jet engine's fuel nozzle illustrated in Figure 1.44 depends on 18 brazed joints along with seven welds that hold it together for consistent operation over thousands of hours of service. Furnace brazing may also include the use of a vacuum, as illustrated in Figure 1.45.

Induction Brazing. Induction brazing (IB) involves heat obtained from resistance to a high-frequency current induced in the workpiece. The workpieces are not connected to the primary electrical circuit. Instead, they are placed in or near a high-frequency coil. The brazing filler metal is usually preplaced. Flux is typically employed, except when using a protective or reducing atmosphere.

The design of the joint and the coil setup must ensure that the surfaces of all joint members reach brazing temperature simultaneously. Joints should be self-jigging rather than fixtured. The metal thickness of components does not normally exceed 1/8 in. (3 mm).

Equipment setup, power supply and controls, and coil design are critical to producing a good quality brazement. When brazing various thicknesses, special attention must be given to coil design and the locations where metal thickness varies. Figure 1.46 illustrates six different ways in which an induction coil can be configured and positioned with respect to the workpieces that are to be heated for brazing.

Photograph courtesy of Parker Hannifin Company

Figure 1.44—Jet Engine Fuel Nozzle Assembly with Brazed Joints

Production speeds are high as heating is accomplished in 4 to 10 seconds. Specially designed coil configurations allow a conveyor belt containing parts to pass through the coil. Induction brazing is commonly used when many parts must be made continuously over a long period. Nonetheless, small shops can handle short-run jobs very economically.

Resistance Brazing. Largely used to braze lap joints, resistance brazing (RB) achieves coalescence using the heat produced by the joint's resistance to electric current transferred to the workpieces by electrodes. The brazing filler metal can be preplaced or face fed. The flux must be partially conductive.

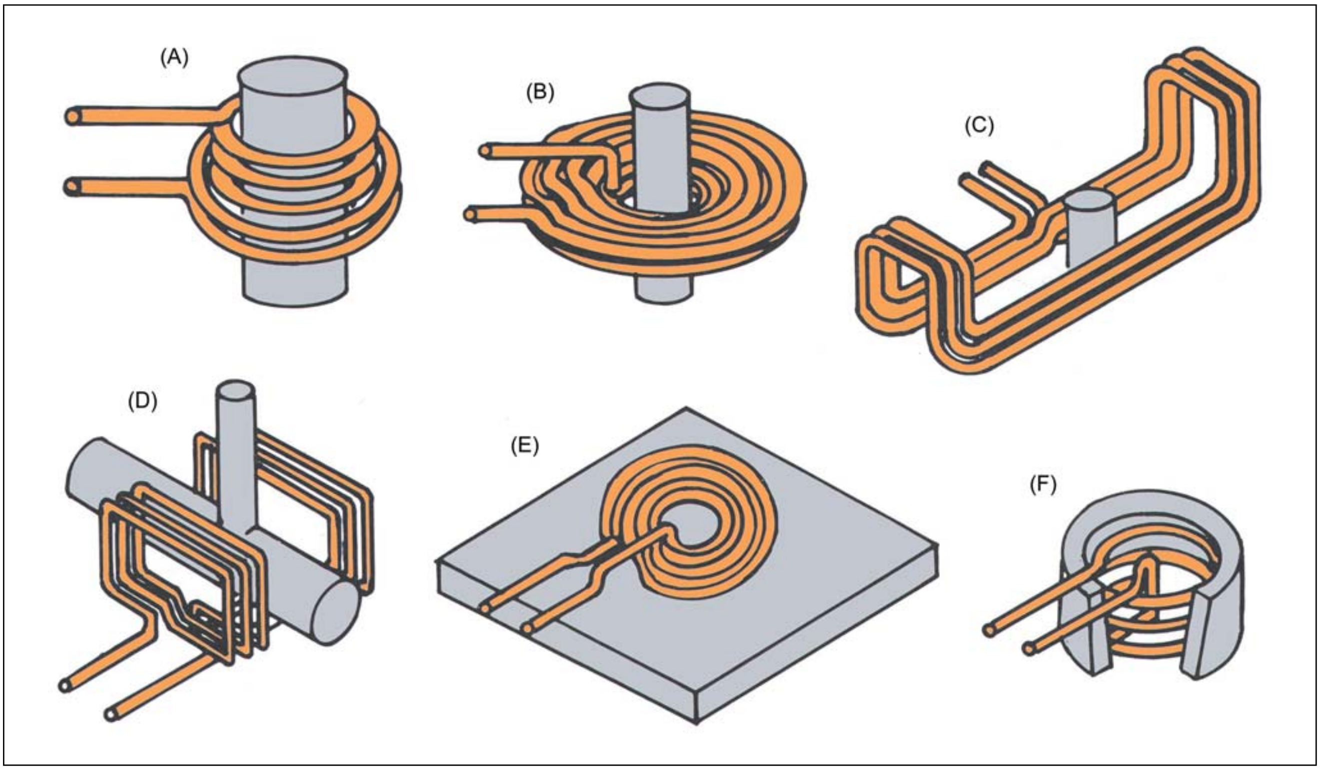
Parts to be brazed are held between two electrodes, which transmit force and current to the joint. Pressure is maintained on the joint until the filler metal has solidified. The thickness of the base metal normally ranges from 0.005 in. to 0.50 in. (0.1 mm to 12 mm).

The cost of resistance brazing equipment depends upon the power required to heat the workpiece to brazing temperature. Cost also varies with the complexity of the electrical controls. Conventional resistance brazing equipment is easy to operate, though more sophisticated equipment may require experience for setup and control operations.

The brazing speed is very fast, especially when the power source and resistance tongs holding the electrode are adequate for the specific joint being made. Resistance brazing is most economical for special application joints that require the heat to be restricted to a very localized area without overheating the surrounding parts.

Figure 1.47 is a photograph of a contact assembly that required a wear-resistant silver-tungsten (Ag-W) contact to be resistance brazed to a formed copper (Cu) part. Figure 1.48 is a photomicrograph of the brazed joint. It shows the contact at the top, the silver-phosphorus filler at the interface, and the copper at the bottom.

Figure 1.45—High-Temperature, High-Vacuum Brazing Furnace



Source: American Welding Society (AWS) Committee on Brazing and Soldering, 1991, *Brazing Handbook*, Miami: American Welding Society, Figure 11.11.

Figure 1.46—Coil Designs for Induction Brazing: (A) External Solenoid; (B) Plate-Type; (C) Conveyor; (D) Split-Solenoid; (E) Pie-Wound; and (F) Internal Solenoid

Dip Brazing. Dip brazing (DB) is a process that accomplishes joining using the heat produced by a molten flux or molten metal bath. When a molten flux bath is used, the bath also provides protection against oxidation. The molten metal bath also provides the filler metal used in the joint.

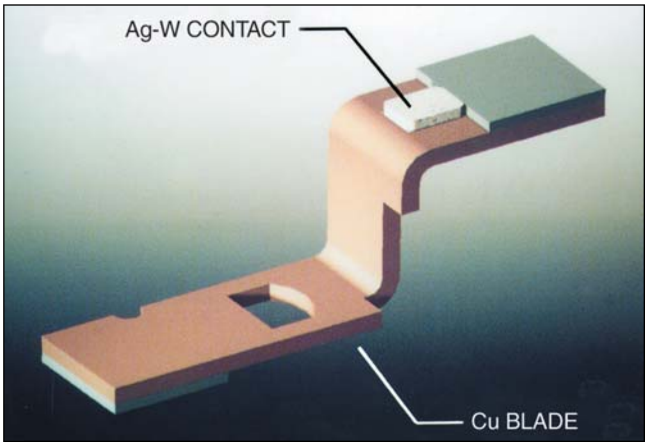
Both types of baths are heated in suitable vessels, containers, or crucibles to furnish and maintain the heat necessary for brazing, provide protection from oxidation, and provide fluxing action if suitable salts are used. The molten flux bath technique is used for most dip brazing applications, which range from thin sheet assemblies to heavier parts and very complex assemblies such as aluminum radiators and other heat exchangers. Careful cleaning of parts before and after brazing is essential.

The dip brazing process, illustrated schematically in Figure 1.49, offers the advantages of ease of operation, excellent production speed, and high efficiency. Since large parts may require that as many as 1000 joints be brazed at one time, dip brazing can be extremely cost effective. However, in the molten metal bath variation, because the entire assembly to be brazed is dipped into the molten bath, dip brazing is limited to small parts that do not lower the temperature in the crucible below that required for brazing.

Infrared Brazing. Infrared brazing (IRB), illustrated in Figure 1.50, uses a high-intensity quartz lamp as the source of heat needed to produce coalescence. The process is particularly well suited for joining very thin materials, such as honeycomb panels for aircraft. It is usually not implemented with sheets thicker than 0.05 in. (1.3 mm).

Assemblies to be brazed are supported in a position that allows the radiant energy of the quartz lamp to be focused on the joint. The assembly and the lamps can be placed in evacuated or controlled atmosphere retorts. The cost of brazing relatively thick joints is comparable to furnace brazing in terms of cycle time, atmosphere, and equipment.

Diffusion Brazing. Unlike the brazing processes discussed previously, diffusion brazing (DFB) is not



Photograph courtesy of LeTourneau University

Figure 1.47—Resistance Brazed Electrical Contact

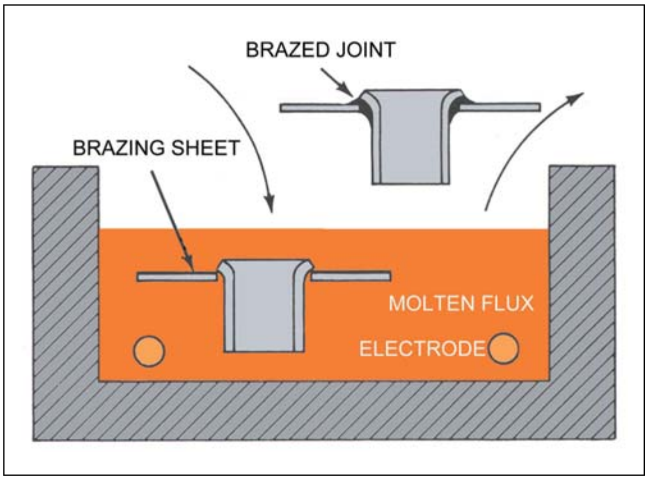
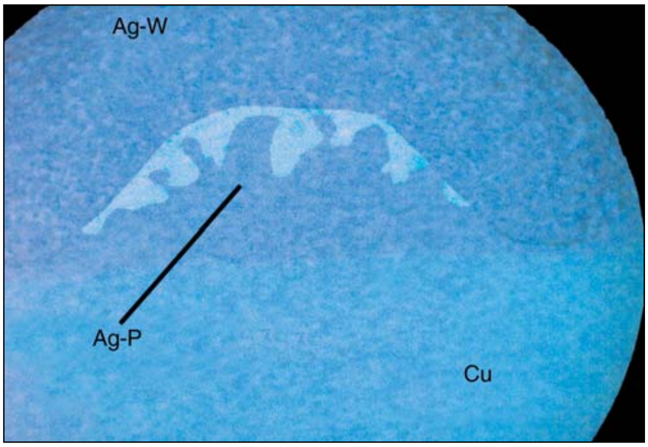


Figure 1.49—Schematic Illustration of Flux Bath Dip Brazing



Photograph courtesy of LeTourneau University

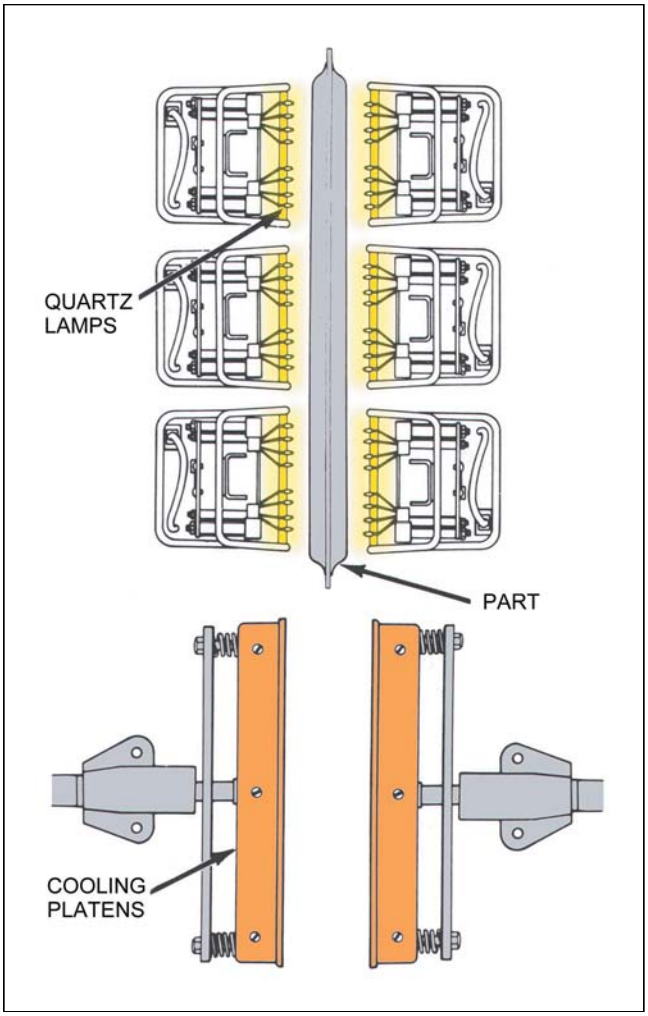
Figure 1.48—Microstructure of the Resistance Brazed Electrical Contact (100X Magnification)

defined by its heat source, which is usually a furnace, but by the diffusion mechanism involved during heating and the application of pressure. In this process, a joint is formed between dissimilar metals by maintaining the brazement at a suitable temperature for a sufficient time for mutual diffusion between the base metal and filler metal to occur. Heating usually occurs in a furnace. While the brazement is held at a constant temperature, the chemical composition of the joint is changed by diffusion. A eutectic composition develops, along with the accompanying low melting temperature. As a result, the joint area temporarily becomes molten. Continued diffusion causes a departure from the eutectic composition. Hence, the melting temperature increases, and the molten metal becomes solid again, forming the brazement.

The equipment used for diffusion brazing is similar to that used for diffusion welding. The joint produced by diffusion brazing has a composition that is considerably different from either the filler metal or the base metal. Although the brazed joint area is indiscernible, it is stronger than the bonds produced by the other brazing processes. Joints produced with this process have a remelt temperature approaching that of the base metal.

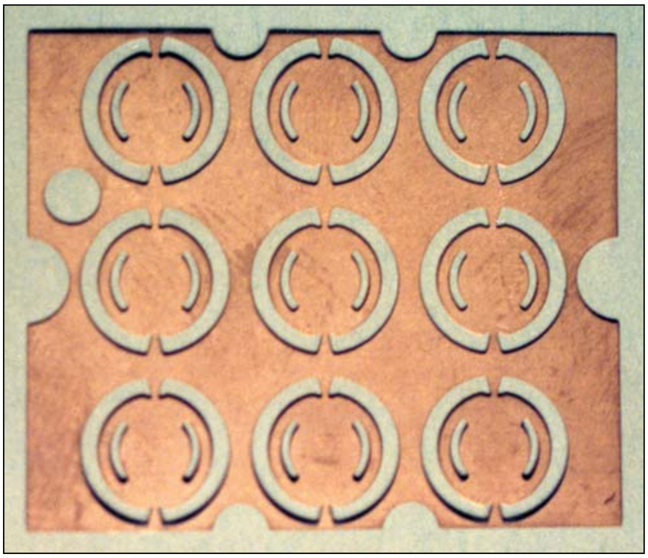
Figure 1.51 presents a photograph of a stamped metal sheet that contains the initial segment of nine jet fuel nozzle swirlers. The sheets are coated by electroless nickel plating, then stacked, weighted, and placed into a furnace. As diffusion occurs at the elevated temperature, transient melting occurs at the sheet interfaces, the weight on the sheets facilitates the bond. This procedure fulfills the liquid-solid phase joining process which by definition is brazing. The nine swirlers are then removed from the diffusion brazed assemblies and installed in fuel nozzles. The 1 in. (25 mm) scale indicates that each swirler is less than 0.3 in. (8 mm) in diameter.

Diffusion brazing offers several advantages. As this process is not sensitive to joint thickness, relatively heavy parts can be brazed. It is applied to base metals ranging from thin foil to sections 1 in. to 2 in. (25 mm to 50 mm) thick. Moreover, many brazements that are difficult to make with other processes can be produced



Source: Adapted from American Welding Society (AWS) Committee on Brazing and Soldering, 1991, *Brazing Handbook*, Miami: American Welding Society, Figure 15.1.

Figure 1.50—Infrared Brazing Apparatus



Photograph courtesy of Parker Hannifin Company

Figure 1.51—Diffusion-Bonded Fuel Nozzle Swirlers

with this method. The parts are usually fixtured mechanically or tack-welded together. Butt and lap joints with good mechanical properties are created. Although diffusion brazing requires a relatively long time (30 minutes to 24 hours) to complete, a number of assemblies can be brazed simultaneously.

Soldering

Soldering (S) involves heating a joint to a suitable temperature and using a filler metal (solder) that is completely molten below 840°F (450°C). The process is used on base metals that are completely solid at the soldering temperature. The solder is distributed between closely fitted joint surfaces by capillary action. Heat is required to raise the joint to a suitable temperature to melt the solder and promote the action of the soldering flux that has been prepositioned on the surface of the metal. This allows the molten solder to wet and flow into the joint. Flux residues may be removed when the joint has cooled.

Soldering is used to join a wide range of metal thicknesses, from very thin films to relatively thick components such as bus bars and pipe. Successful soldering requires the shaping of parts to fit closely together. The surfaces to be joined must also be cleaned.

The variations of the soldering processes are defined by the source or method of heating used in each. Soldering processes widely used in industry are dip (DS), iron (INS), resistance (RS), torch (TS), induction (IS), furnace (FS) infrared (IRS), ultrasonic (USS), wave (WS), and cascade soldering (CS). Most of these are similar in application to the brazing methods described above. Dip, wave, and cascade soldering are illustrated in Figure 1.52.

Automated soldering equipment produces the highest quality joints at a low cost. Wave and cascade soldering are automated processes. They are often used by the electronic industry to produce many high-quality soldered joints simultaneously. For example, circuit boards are commonly soldered using the wave or

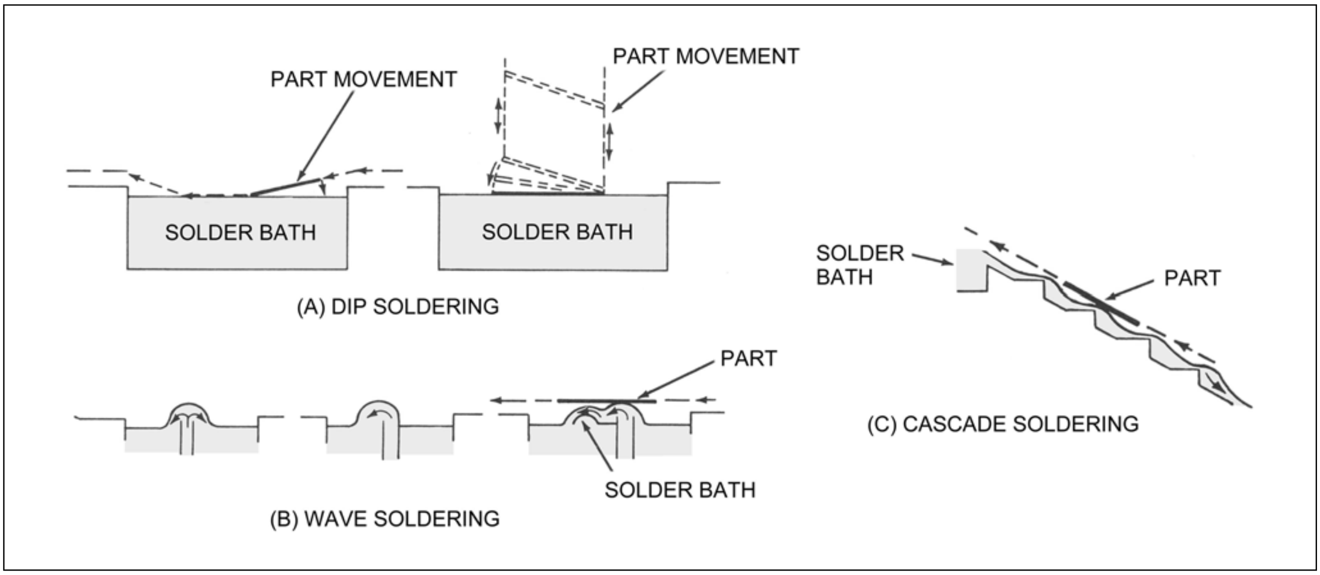


Figure 1.52—Schematic Illustration of (A) Dip Soldering; (B) Wave Soldering; and (C) Cascade Soldering

cascade methods. On the other hand, manual soldering with a traditional copper-tipped soldering iron is a relatively slow process requiring a certain degree of skill, especially when soldering crucial electronic equipment or complex or critical components. It is economical when production rates are low. Manual dip soldering, which is much faster than manual soldering, is useful for moderate production requirements. A high degree of operator skill is not required for automated soldering such as wave or cascade soldering.

Braze Welding

Braze welding (WB) is a joining process that accomplishes coalescence using a filler metal with a liquidus above 840°F (450°C) and below the solidus of the metal. Braze welding is different from brazing in that the filler metal is not distributed throughout the joint by means of capillary action.

Normally performed with an oxyfuel gas torch, braze welding is carried out at a lower temperature than welding since the base metal is heated only enough to melt the filler metal. For example, a brazing filler metal typically used to repair cast iron is completely molten at 1650°F (899°C), which is about 1000°F (538°C) below the melting temperature of cast iron.

Braze welding is typically used to repair cracked or broken gray iron castings or to salvage other broken items. A groove is usually prepared by grinding out the defect, or a fillet joint may be used to add an additional reinforcing member to the salvage job. If a single pass is not sufficient to complete the repair, multiple passes are used. In this case, each successive pass welds onto the previous passes, but the bond to the base metal is created by diffusion since this metal remains solid throughout the process. The filler metal used for braze welding is more viscous than that employed for brazing. This higher viscosity permits the metal to build up, forming a weld-type deposit, rather than flow as would be required to fill the capillary-type joint used for brazing.

CUTTING PROCESSES

The selection of a cutting method has important implications. As with choosing the best joining method, potential cutting methods must be investigated and evaluated with respect to the priorities that are established for the application. The objective is to choose the best method based on a consideration of economy, process capability, and the effects on the material to be cut.

Although thermal methods are usually the most economical and offer the greatest productivity, some materials are adversely affected by the significant heat produced by these methods. Nonthermal methods are usually slower, but they can be used with precision on a wide variety of metals and nonmetals.

THERMAL CUTTING

The thermal cutting (TC) processes accomplish the severing or removal of metal by means of localized melting, burning, or vaporizing of the workpiece. Though all utilize heat to accomplish the cut, each process has a different principle of operation. The various processes also have different applications with respect to materials and thicknesses.

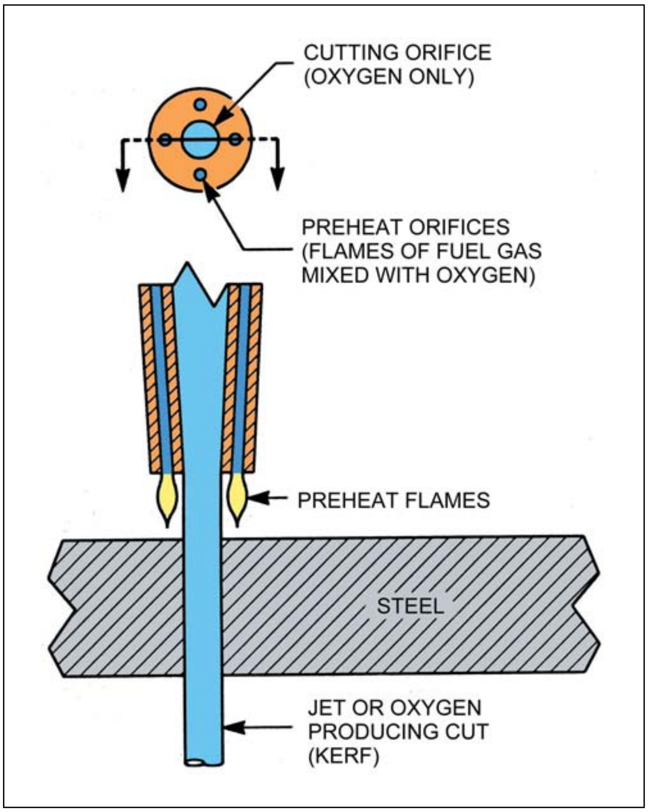
The thermal cutting processes most widely used in industry are oxyfuel gas (OFC), plasma arc (PAC), air carbon arc (CAC-A), and laser beam cutting (LBC). Table 1.2 presents an overview of their capabilities.

Oxyfuel Gas Cutting

The oxyfuel gas cutting (OFC) processes utilize the heat produced by an oxyfuel flame to accomplish cutting. In this process, the metal to be cut is heated to its kindling temperature (the temperature at which steel rapidly oxidizes) using a fuel gas-oxygen mixture (the most widely used fuels are acetylene, natural gas, propane, and other special formulations). At this point, a high velocity stream of oxygen is introduced, and rapid oxidation (burning) takes place. The reaction quickly penetrates the thickness of the steel workpiece, with some of the molten metal being blown out underneath. Illustrated in Figure 1.53, these processes are used extensively in the severing or gouging of carbon steel.

To perform a cut with oxyfuel gas cutting, the metal must react with oxygen to produce an oxide. The oxide must have a melting temperature that is lower than that of the metal being cut. If an oxide with a very high melting temperature, termed a *refractory oxide*, develops, it acts as a protection from further oxidation. This protection barrier renders the process ineffective. Refractory oxides develop when performing oxyfuel gas cutting with materials such as stainless steels.

The cutting tips used are designed to provide a ring of oxyfuel gas flames. These flames preheat the metal to its kindling temperature. The cutting tips are also designed to produce a small-diameter, high-velocity stream of oxygen to oxidize and remove metal, producing a narrow cut or kerf in the steel. The torch is moved at a speed that maintains an acceptable cut quality. The quality and speed of the cut depend on the design and size of the torch tip, the distance from the steel surface, the travel speed, oxygen, and the fuel gas pressures and resulting flow rates. All these variables must be regulated for the particular material type and thickness being cut.



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.82.

Figure 1.53—Schematic Representation of Oxyfuel Gas Cutting

Table 1.2 Applicability of Thermal Cutting Processes to Materials*

	Cutting Processes†			
Material	**OFC**	**PAC**	**CAC-A**	**LBC**
Carbon steel	x	x	x	x
Stainless steel	x‡	x	x	x
Cast iron	x‡	x	x	x
Aluminum		x	x	x
Titanium	x‡	x	x	x
Copper		x	x	x
Refractory materials		x	x	x

*This table should be regarded as only a very general guide to process applicability. For processes to be used with specific alloys, the manufacturer or other appropriate sources should be consulted.

†OFC = oxyfuel gas cutting; PAC = plasma arc cutting; CAC-A = air carbon arc cutting; and LBC = laser beam cutting.

‡Process applicable with special techniques. All other processes (x) are commercially applied.

The travel speed employed in oxyfuel gas cutting depends upon the type and thickness of material and the characteristics of the oxyfuel gas flame. For relatively thin steel of less than 1/2 in. (12 mm), the travel speed is limited by the speed at which the kindling temperature can be reached and maintained in front of the cut. Thus, for thinner metals, the oxyfuel gas mixture that yields the hottest and most concentrated flame—oxyacetylene—is ideal. When cutting thick steel, the speed of travel is limited by the speed at which the oxidation can penetrate through the steel. For thicker metals, a more diffused flame with a lower temperature is ideal. This kind of flame prevents the top edge of thicker metals from becoming overheated.

Cutting torches and tips are designed for specific fuel gases or groups of fuel gases. Injector designs are used for fuel gas pressures of less than 2 pounds per square inch (lb/in.^{2}) (14 kilopascal [kPa]), whereas positive pressure designs are utilized for fuel gas pressures of more than 2 lb/in.^{2} (14 kPa). Some cutting tips are designated for use with standard speed and standard pressure; others are high-speed, high-pressure tips.

Oxyfuel gas cutting is often applied in the cutting of mild steel plates. Theoretically, no limit exists with respect to the maximum thickness that can be cut with this process. High-quality industrial cuts have been made in metal more than 2 ft (600 mm) thick. However, a metal thickness of less than 1/4 in. (6 mm) is often distorted because of the localized heating.

Alloyed steels are more difficult to sever. The speed, quality, and even the feasibility of cuts in alloyed steel depend on the alloy type and amount present. Stainless steels cannot be cut with the standard oxyfuel cutting torch because they develop refractory oxides during the process. To sever stainless steel using oxyfuel gas cutting, flux can be added to neutralize the protective refractory oxides or iron can be added to reduce the chromium content. At greater than 11%, chromium is the main element alloyed with iron to produce the corrosion resistance characteristic of stainless steels. When stainless steel is cut using the oxyfuel gas method, refractory oxides quickly form, preventing rapid oxidation from continuing. The chromium content can be reduced by injecting iron powder into the cutting stream or placing a mild steel waster plate on the surface of the metal to be cut.

Modifications of oxyfuel gas cutting equipment are used for scarfing metal, gouging U-grooves, removing defective welds, and beveling plate edges in preparation for welding. Equipment has also been developed to allow the cutting of sheets or thin plates of steel stacked approximately 2 in. (50 mm) high.

Manual oxyfuel gas cutting operations are often selected for implementation because personnel can be trained to operate the equipment in a short time. However, considerable skill is necessary to produce high-quality manual cuts and bevels suitable for welding. The skill requirements for single or multitorch mechanized equipment are dependent on the application, the edge configuration desired, and the technical capability of the equipment. Equipment controlled by computer or electronic tracing can shape-cut many parts at once, depending on the number of torches on the machine.

Plasma Arc Cutting

Plasma arc cutting (PAC), illustrated in Figure 1.54, is accomplished with an extremely hot, high-velocity plasma jet formed by an arc and the ionized gas flowing from a constricted orifice. The arc-gas plasma energy is concentrated on a small area of the workpiece, where the arc-gas plasma melts the metal and forces the molten metal through the kerf and out beneath the metal. Light- to medium-duty plasma arc cutting systems use compressed air as the plasma gas. Heavy-duty systems typically use nitrogen or an argon-hydrogen mixture for the plasma gas, and carbon dioxide or an inert gas as the secondary or shielding gas.

Plasma arc cutting can incorporate the use of water in several ways. Water can be injected into the plasma orifice to supplement the super heat. It can also be used as a shroud around the arc to minimize noise, pollution, and arc brilliance. The metal can also be submerged in water contained in a cutting table tank to minimize the heat-affected zone and distortion.

A versatile process, plasma arc cutting is capable of cutting all metals, both ferrous and nonferrous. Mild steel can be severed two to three times faster with this process than with oxyfuel gas cutting. However,

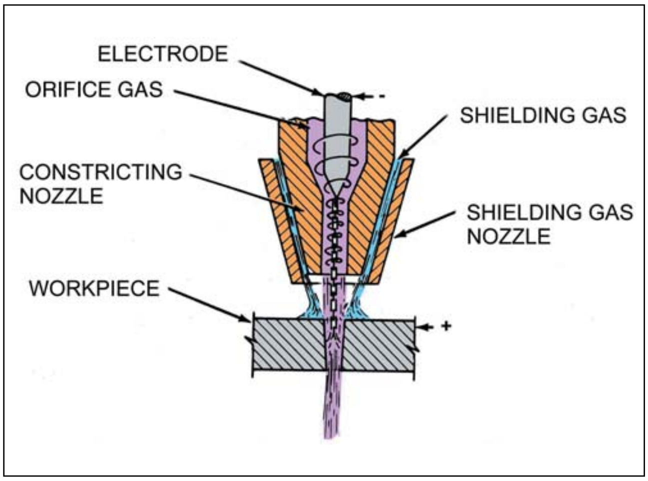


Figure 1.54—Schematic Representation of Plasma Arc Cutting

because more metal is removed from the top surface than from the bottom, the kerfs are wider and somewhat tapered. Special nozzles are designed to cut a square edge on one side of the kerf, leaving the entire taper on the other side.

Plasma arc cutting torches are available for manual cutting. Like oxyfuel gas cutting, manual plasma arc cutting is easy to learn, but difficult to perfect, especially when making cuts suitable for welding. Compressed-air plasma arc cutting machines readily make clean cuts on thin-gauge materials, such as those used for vehicle bodies. Mechanized equipment is extensively used for industrial applications, cutting metal up to about 3 in. (75 mm) thick. Plasma arc is also a viable process for gouging.

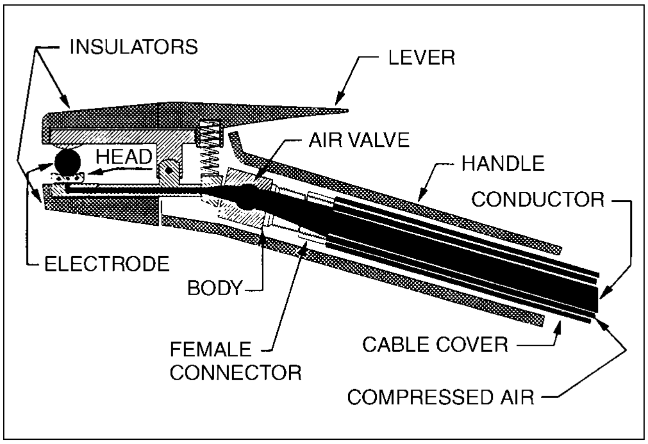


Figure 1.55—Manual Air Carbon Arc Electrode Holder with Electrode

Air Carbon Arc Cutting

Air carbon arc cutting (CAC-A) uses an arc to melt the metal, which is subsequently blown away by a high-velocity jet of compressed air. This process is applicable to most metals, as indicated in Table 1.2.

The electrodes used in air carbon arc cutting operations are made from carbon. They are coated with copper to enhance their current-carrying capacity. Standard constant-current welding power sources of sufficient capacity for the electrode size are used to provide the current. The electrodes used to perform the air carbon arc gouging of U-grooves are normally larger than those used for shielded metal arc welding; thus, the current demands are greater. Air is normally supplied by conventional shop air compressors, which can maintain flow rates of 20 cubic feet per minute (ft^3/min) to 30 ft^3/min (600 liters per minute [L/min] to 900 L/min) at 80 lb/in.^{2} (550 kPa).

Manual air carbon arc cutting electrode holders, like the one shown in Figure 1.55, resemble the holders used in shielded metal arc welding. However, air carbon arc cutting holders are equipped with two to three orifices to permit the air jet to flow through and blow away the molten metal produced by the arc. To ensure that the air jet can effectively blow away molten metal, the copper-coated carbon electrode should be held 3 in. to 4 in. (76 mm to 100 mm) away from the arc. As the electrode sublimates, becoming shorter, it can be repositioned as desired.

In gouging operations, the depth and contour of the groove are controlled by the electrode angle, travel speed, and current. Grooves up to 5/8 in. (16 mm) deep can be made in a single pass. In severing operations, the electrode is held at a steeper angle and directed at a point that will permit the tip of the electrode to pierce the metal being severed.

Semiautomatic or fully automatic air carbon arc cutting equipment has the capacity to cut U-grooves of virtually uniform geometry. In manual work, the geometry of U-grooves is dependent on the skill possessed by the cutting operator. Manual techniques are more suitable than automatic methods for removing weld defects or severing excess metal from castings. Manual air carbon arc cutting operators must be trained to avoid shorting the electrode, which can deposit carbon particles in the metal. These particles can create very hard spots in the metal, leading to cracks or machining difficulties.

Laser Beam Cutting and Drilling

Laser beam cutting (LBC) is a thermal cutting process that accomplishes a cut by locally melting and vaporizing material with the heat produced by a laser beam. The process is used with or without an assisting gas, which helps remove molten or vaporized material. Figure 1.56 illustrates the laser beam cutting process. The equipment used to produce the laser beams is described in the section on laser beam welding.

Among the applications of the laser beam process, cutting is the most common, enjoying an excellent growth rate worldwide. Internationally, laser cutting and the related processes of drilling, trimming, and scribing account for more than 50% of industrial laser installations. A high-power carbon dioxide laser can cut steel up to 1 in. (25 mm) thick. However, good quality cuts are typically made on metal thinner than 3/8 in. (9.5 mm). Neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers are also used. Depending on the material, a jet of reactive gas such as oxygen can be applied coaxially with the beam, improving process speed and cut edge quality.

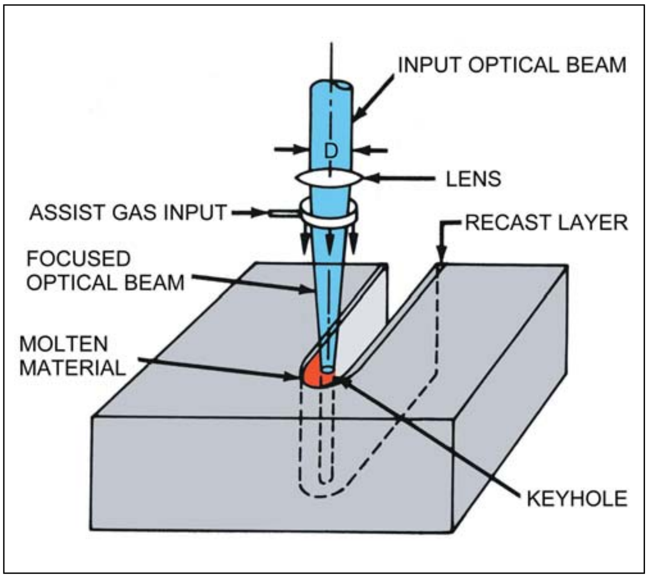


Figure 1.56—Schematic Illustration of Laser Beam Cutting

Laser beam cutting offers the advantages of high-speed production, narrow kerfs, low heat input, and minimal workpiece distortion. An easily automated process, it can be used to cut most materials. Finishing operations are usually not required. It also is advantageous for short production runs. Noise, vibration, and fume levels are quite low. Relative movement between the beam and the workpiece can easily be programmed using computer numerical control (CNC) workstations. High precision and good edge quality are common even in three-dimensional laser beam cutting.

Laser beam drilling is closely related to cutting. Drilling involves higher beam densities and shorter dwell times than laser cutting. The high-intensity pulsed output from the solid-state lasers with shorter wavelengths (e.g., the Nd:YAG lasers) is more suitable for drilling metals. Carbon dioxide lasers are typically used to drill nonmetallic materials such as ceramics, composites, plastics, and rubber. Laser drilling is cost effective for producing holes less than 1 in. (25 mm) deep and up to 0.060 in. (1.5 mm) in diameter. In this range, laser beam drilling is a cost-effective alternative to mechanical, electrochemical, and electrical discharge machining.

Laser beam material processing equipment is expensive, however. The equipment also requires skilled operators with a good knowledge of this sophisticated equipment and laser-material interaction. With the increased use of the process, the price of laser cutting systems may decrease somewhat in the future.

WATER JET CUTTING

Water jet cutting uses a high-velocity water jet to cut a variety of materials, including metals and nonmetallic materials. The water jet is formed by forcing water through a 0.004 in. to 0.024 in. (0.1 mm to 0.6 mm) orifice in a manufactured sapphire under a high pressure of 30 ksi to 60 ksi (207 MPa to 414 MPa). Although water jet cutting is not a thermal cutting process, it is somewhat related inasmuch as a kerf is produced by concentrated water jet erosion.

The principles of the various thermal cutting processes previously described in this chapter differ in the way energy is utilized to sever materials. In water jet cutting, water—sometimes with an abrasive additive—is used to erode the material to effect the cut, thus making a kerf in the same manner as the thermal methods. As a machine tool cutting device is not employed in water jet cutting, this process is more closely related to the thermal cutting techniques than to machine tool methods.

Figure 1.57 illustrates a stack of dissimilar materials—including carbon steel, brass, copper, aluminum, and stainless steel—being cut. An abrasive jet is particularly effective for cutting laminates of different materials, including sandwiched sections of metals and nonmetals. As the abrasive jet is capable of penetrating most materials, predrilling usually is not required. Table 1.3 lists the cutting procedure variables for nine nonmetallic materials.

The two types of water jet cutting are simple water jet cutting and abrasive water jet cutting. Simple water jet cutting uses only water, while abrasive water jet cutting uses water mixed with an abrasive grit. In simple water jet cutting, tapered cuts are typically encountered because the water has a tendency to spread as it leaves the orifice. Kerf tapering may be reduced by adding long-chain polymers such as polyethylene oxide to the water or by decreasing travel speed. With abrasive water jet cutting, tapered kerfs are usually not encountered unless the cutting speed is too fast, the workpiece is too thick, or an excessively worn nozzle has been used.

The orifice nozzle, normally the only part that wears, requires replacement every 2 to 4 hours of constant operation. Cuts are usually clean, and minimal deburring, if any, is needed on many applications. Minimal lateral forces are generated, simplifying fixturing. The process is readily adaptable to robotic control.

Water jet cutting has several limitations. It is capable of only relatively low cutting speeds. In addition, the pumps and pressure chamber required to propel and direct the water jet are expensive, so initial capital investment is high. A device must also be provided to collect the discharge from the cutting stream, and the discharge requires proper disposal. Materials cut must be softer than the abrasive used. In addition, bending on very thin ductile metals may result from the force of the abrasive jet, producing burred edges.

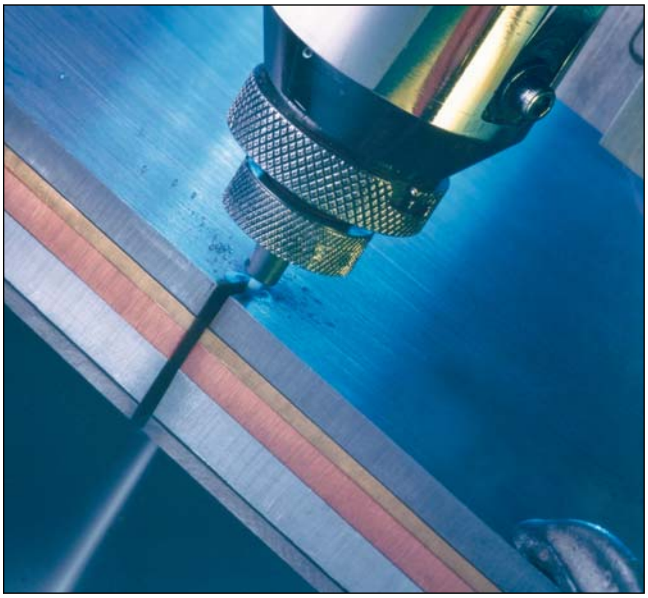


Figure 1.57—Water Jet Cutting of Dissimilar Materials

Table 1.3
Water Jet Cutting Speeds for Various Materials

	Thickness		Travel Speed	
Material	in.	mm	in./min	mm/s
ABS plastic	0.080	2.0	80	34
Cardboard	0.055	1.4	240	102
Corrugated cardboard	0.250	6.4	120	51
Circuit board	0.103	2.6	100	42
Leather	0.063	1.6	3800	1600
Acrylic resin or plastic	0.118	3.0	35	15
Rubber	0.050	1.3	3600	1500
Rubber-backed carpet	0.375	9.5	6000	2500
Wood	0.125	3.2	40	17

THERMAL SPRAYING

The thermal spraying (THSP) processes deposit metallic or nonmetallic surfacing materials in a molten or semimolten state on a substrate to create a thermal spray deposit. In these processes, metallic or nonmetallic material is heated and then propelled from a gun nozzle by a gas jet. The material is propelled in atomized form onto the substrate. Initially, the surfacing material may be in the form of wire, rod, or powder. Methods of heating the surfacing material to the plastic or molten state include an oxyfuel gas flame, as illustrated in Figure 1.58, an electric arc, a plasma arc, or an explosive gas mixture. Most metals, cermets (ceramic-metal mixtures), oxides, and hard metallic compounds can be deposited using one or more process variations. Thermal spraying can also be employed to produce freestanding objects using a disposable substrate.

Compressed air, which causes oxides to form on each particle (oxidation), is used with some thermal spraying methods to propel the molten particles across a distance. Even when compressed air is not used, oxidation occurs merely from the ambient air present between the nozzle and substrate. When molten particles strike a substrate, they flatten and form thin platelets that conform to the surface. These platelets rapidly solidify and cool. Successive layers are then built up to create the desired thickness.

The bond between the spray deposit and the substrate, though metallurgical to some extent, is primarily mechanical. The degree of strength of each bond depends upon the thermal spraying method and procedure used. In some cases, a postspray fusion heating operation on the spray deposit enhances particle coalescence and bond strength, causing a diffusion or chemical reaction between the sprayed deposit and the substrate. The properties of the deposit depend upon its density, the cohesion between the deposited particles, and adhesion to the substrate.

Thermal spraying is widely used in surfacing applications to attain or restore desired dimensions; to improve resistance to abrasion, wear, corrosion, oxidation, or a combination of these; and to provide specific electrical or thermal properties. Thermally sprayed deposits are frequently applied to new machine elements to provide surfaces with desired characteristics for the application.

A variety of different thermal spraying methods, including flame (FLSP), arc (ASP), plasma (PSP), and detonation flame spraying, are categorized according to the method used to heat the surfacing material. The combustion and electrical methods both involve the heating of the spray material to the molten or plastic state and then the propelling of the atomized material onto the substrate. Most thermal spraying applications utilize mechanized systems.

FLAME SPRAYING

In flame spraying (FLSP), illustrated schematically in Figure 1.58, the surfacing material is continuously fed into and melted by an oxyfuel gas flame. The material may initially be in the form of wire, rod, or powder. Molten particles are projected onto a substrate by an air jet or gas combustion. Figure 1.59 illustrates oxyfuel

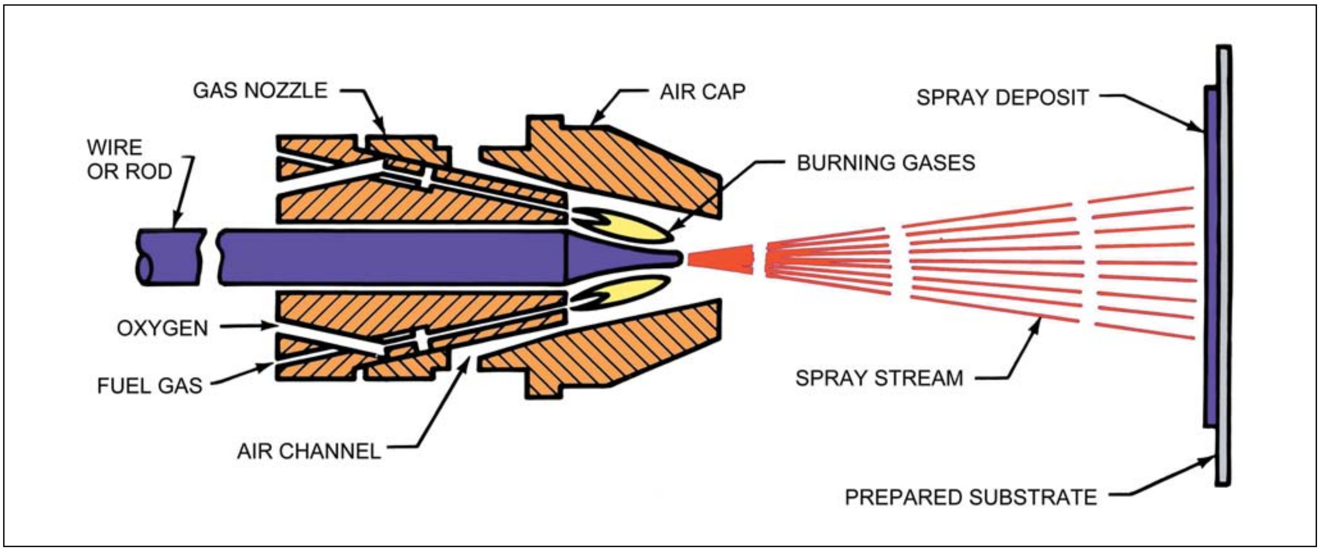


Figure 1.58—Schematic of Oxyfuel Gas Flame Spraying

Figure 1.59—Oxyfuel Gas Spraying

gas flame spraying with a hypervelocity powder flame spray torch.

PLASMA ARC SPRAYING

In plasma arc spraying (PSP), the heat required to melt the surfacing material is provided by a nontransferred plasma arc. The arc is maintained between an electrode that is usually made of tungsten and a constricting nozzle. An inert or reducing gas, under pressure, enters the annular space around the electrode along with the surfacing powder. The nontransferred arc on the electrode heats the powder and gas to a temperature above 15,000°F (8300°C). The hot plasma gas and heated powder particles pass through the constricted orifice and are propelled from the nozzle at a very high velocity. The particles impact the substrate to create a denser deposit and stronger bond than is possible with the oxyfuel gas or arc thermal spraying method.

ARC SPRAYING

Arc spraying (ASP) utilizes an arc formed between two continuously fed electrode wires. This arc melts the metal electrode wire. Then, compressed air propels the molten particles to the substrate. Capable of deposition rates exceeding 100 lb/hr (45 kg/hr), this is the fastest thermal spraying method available. A schematic of wire arc spray is shown in Figure 1.60.

DETONATION FLAME SPRAYING

Shown in Figure 1.61, the detonation flame spraying (DFSP) method operates on a principle that is significantly different from the other three methods. In this process, rapid, successive detonations of an explosive mixture of oxygen and acetylene occur in a gun chamber. The detonation repeatedly heats charges of powder and projects the molten particles onto a substrate. The particles exit the gun at a much higher velocity than

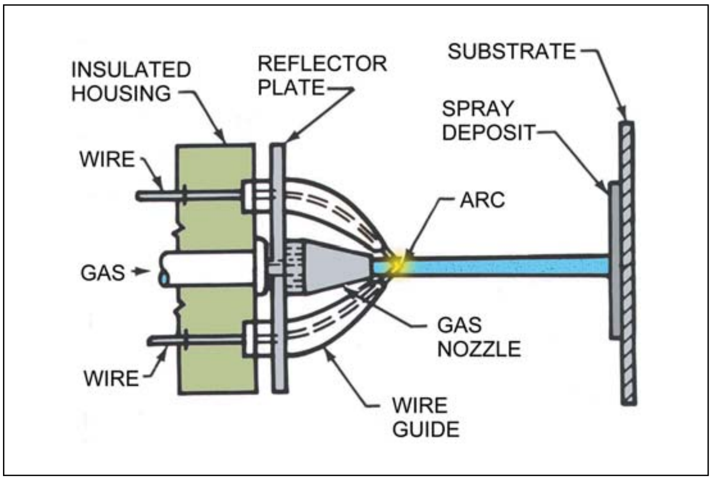


Figure 1.60—Schematic Illustration of Arc Spraying

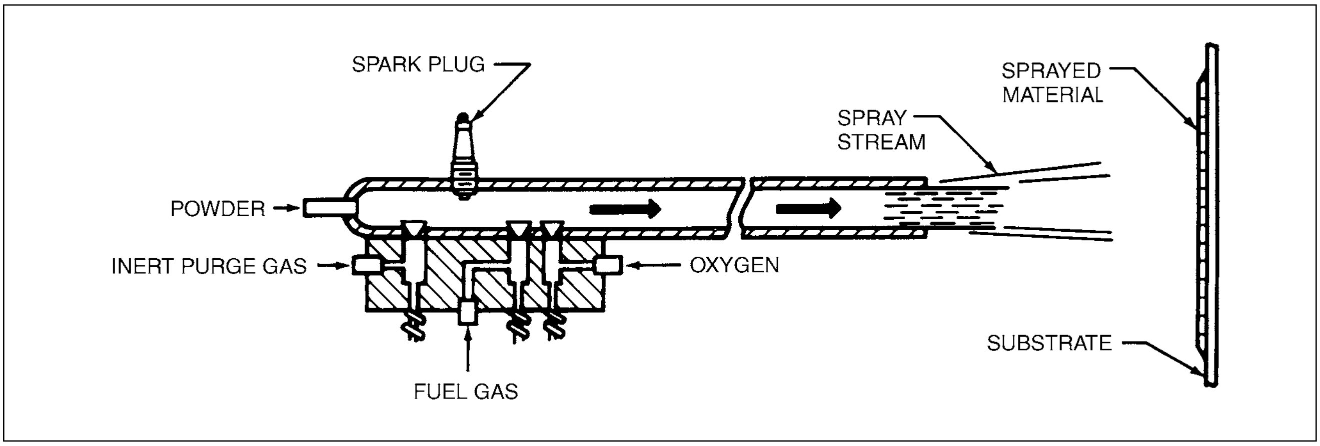


Figure 1.61—Schematic of Oxyfuel Gas Gun for Detonation Flame Spraying

that utilized in the other methods, producing a dense deposit that has a strong bond with the substrate.

CONCLUSION

This chapter describes the most important welding, cutting, and allied processes in use in industry. Before making final decisions regarding process selection for an application, an objective, in-depth study and a thorough investigation should be made. Process selection has major implications with respect to manufacturing costs. Inasmuch as equipment costs can vary from a few hundred to millions of dollars, the cost of equipment versus production volume must be carefully evaluated. The right decisions regarding equipment selection can result in great rewards, including remaining competitive in the global market.

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CHAPTER 2

PHYSICS OF WELDING AND CUTTING

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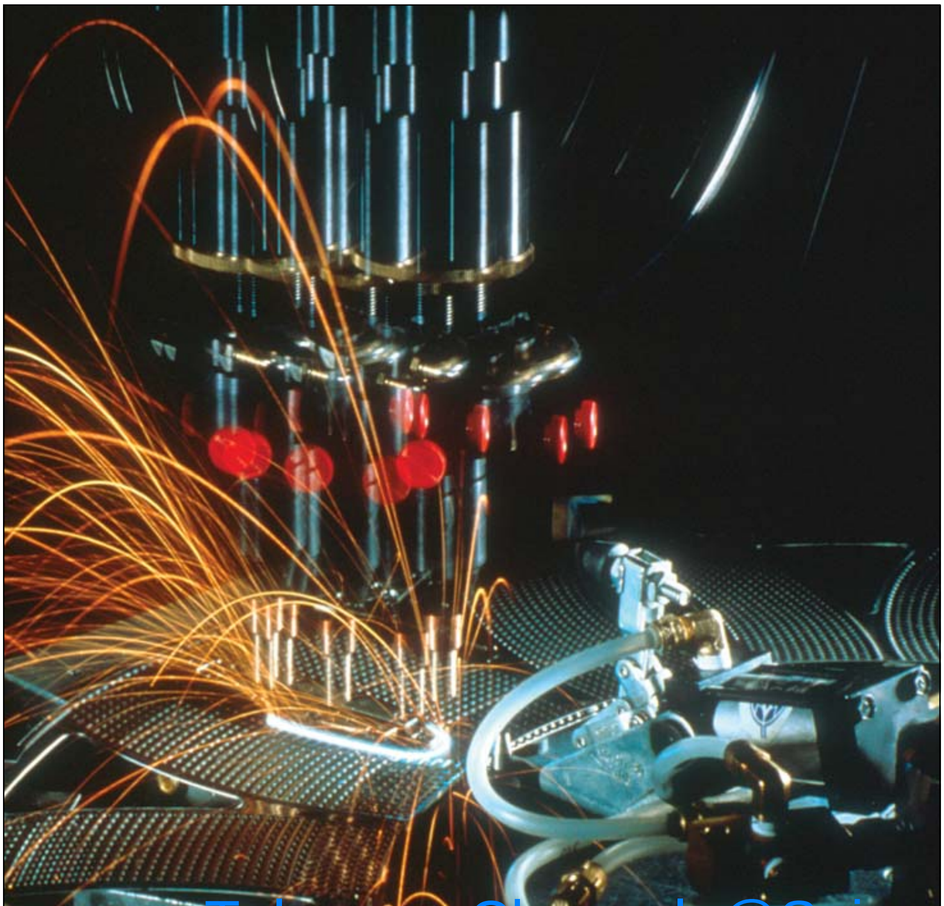

Photograph courtesy of Coherent General, Incorporated

Contents

CHAPTER 2

PHYSICS OF WELDING AND CUTTING

INTRODUCTION

The physics of welding deals with the phenomena associated with welding processes and the formation of weld bonds. This chapter discusses two types of welds, fusion welds and solid-state welds. These are commonly differentiated by the physics of the metallic bonding mechanism.

The chapter includes a discussion of the physics of energy sources—electrical, chemical, focused-beam, mechanical, and solid-state—and energy transfer as they relate to the various welding processes. Also discussed are the physical phenomena of the electric arc, metal transfer, melting rates, the properties of metals and shielding gases, and the manner in which these and myriad associated phenomena contribute to successful (or unsuccessful) welds.

The information in this chapter is applicable to many thermal cutting and spraying processes, as they are closely allied with welding processes and involve the same phenomena for the purposes of cutting or removing material, cladding, and surfacing. Considering that the International System of Units (SI) is customarily employed in this discipline, this chapter uses SI units exclusively.

FUSION AND SOLID-STATE WELDING

The physics of weld bonds and the associated welding processes differ markedly with respect to fusion welds and solid-state welds and are best considered separately. Fusion welds are created by the coalescence of molten base metals mixed with molten filler metals (if a filler metal is used). Metals must be heated to the melting point for fusion welds to be produced. Solid-state welds are produced at temperatures below the melting temperature and are created by either the macroscopic or microscopic coalescence of the materials in the solid state.

FUSION WELDS

Fusion welding processes must produce sufficient heat to achieve melting. Heat for melting is either developed at the intended weld joint or applied to the intended joint from an external source. In some processes, pressure is applied to force the materials into close contact. An example of a means of developing heat at the weld joint is the passing of current through the electrical contact resistance between the contacting surfaces of the materials to be welded (resistance welding). Electrical discharges between surfaces can also be utilized to develop heat for joining (flash welding). A common characteristic of these welding processes is that the entire weld is usually produced at one time, either at a spot or along an entire joint.

Most fusion welding processes apply heat from an external source to the weld joint to produce the weld bond. Heat is transported from the heat source to the joint by conduction, convection, and radiation. Almost every imaginable high energy density heat source has been adapted at one time or another for fusion welding.

Sources of externally developed heat include electron beams, laser beams, exothermic chemical reactions (used in oxyfuel gas welding and thermite welding), and electric arcs. Fusion welding processes that apply heat from external sources are usually identified according to the type of heat source employed. Electric arcs, the most widely used heat source, are the basis for the various arc welding processes. The following are the most commonly used processes that operate with external heat sources:

Shielded metal arc welding (SMAW),
Gas metal arc welding (GMAW),
Flux cored arc welding (FCAW),
Gas tungsten arc welding (GTAW),
Electrogas welding (EGW),
Plasma arc welding (PAW),
Submerged arc welding (SAW),
Electroslag welding (ESW),
Oxyacetylene welding (OAW),
Thermite welding (TW),
Laser beam welding (LBW), and
Electron beam welding (EBW).

As usually implemented, a heat source is applied to the prepared edges to be joined and moved along the intended joint. The welded joint is formed over the period of time required for the heat source to traverse the length of the joint. The energy density of the heat source must be sufficient to accomplish local melting. Filler metal may be added, in which case the heat source must also melt the filler metal as it is delivered to the joint.

The transferred power of a heat source is the rate at which energy is delivered per unit time from the heat source to the workpiece, typically expressed in joules per second (J/s) or watts (W). The terms *power density* and *energy density* are often used to describe the transferred power per unit area of effective contact between the heat source and the workpiece, generally expressed in watts per square meter (W/m^2) or watts per square millimeter (W/mm^2).[1] Energy density is an unambiguous measure of "hotness" that is applicable to all kinds of heat sources.[2]

The evolution of the fusion welding processes has been predicated, in large measure, on the development and adaptation of heat sources that produce higher and higher energy densities. Thus, the oxyacetylene flame, as used for welding, has been almost completely displaced by the higher-energy-density electric arc. Plasma arc, electron beam, and laser beam welding are more recently developed welding processes that exhibit even higher energy density than conventional arc welding. These processes find use mainly in specialized applications and are not widely competitive with conventional arc processes.

The transfer of energy to a workpiece from an arc, a flame, an electron beam, or a laser beam is a complex process. It is difficult to define precisely the area of contact between the heat source and the workpiece. In addition, the intensity of the heat is distributed nonuniformly over the contact area, typically exhibiting a maximum intensity near the center. Thus, the detailed nature of energy transfer is quite complicated, but the concept of energy density contributes much to the understanding and comparison of welding heat sources.

The heat produced by a welding heat source such as an arc occurs in two stages.[3] First, heat is transferred from the source to the surface of the workpiece. Then, heat is transferred within the workpiece from the contact area to colder regions of the materials to be joined.

With a very high energy density heat source such as an electron beam, a high power beam is delivered to a very small contact area. Substantial local melting occurs due to the high temperature required to drive heat conduction through the small conduction area surrounding the point of heating. At the other extreme, a very low-energy-density source, such as an oxyfuel gas flame, transfers a large quantity of power to the workpiece, but over a large contact area. Due to the large available conduction area surrounding the point of heating, a lower surface temperature is required, and melting may not occur. The effectiveness of a welding heat source thus depends fundamentally on the energy density of the source.

Energy Input

Another important heat source measure that is fundamental to the study of heat flow in welding is the concept of *energy input* of the heat source. Energy input is the quantity of energy applied per unit length of weld. It is expressed in joules per meter (J/m) or joules per millimeter (J/mm). In the case of arc welding, it is termed *arc energy input*.

The energy input is mostly used for its relationship to the weld cooling rate, and thus to the metallurgical and mechanical properties of the weld. The study of heat flow with a traveling heat source presented in Chapter 3 of this volume discusses the manner in which weld cooling rates are predicted by theory to be inversely proportional to the net energy input (for a moving heat source on a thick plate).

1. The terms *power density* and *energy density* are commonly used in welding to describe the rate of energy (power) deposited by a heat source per unit of area of contact with the heated surface, for instance, in W/mm^2. The use of the terms *energy* and *density* is somewhat inconsistent. Power or heat intensity, or energy flux, are more accurate terms, but the terms *energy density* and *power density* are strongly embedded in the welding nomenclature and will be used herein.
2. Heat sources are sometimes qualitatively compared in terms of temperature, which is a satisfactory index for gas flames, but it would be meaningless to speak of the "temperature" of an electron or laser beam. Even the heating capacities of welding arcs are not well characterized by temperature.

3. Heat flow in welding is discussed in Chapter 3 of this volume.

The energy input for a traveling heat source is computed as the ratio of the total heating power of the heat source in watts to its travel velocity, as follows:

$$H = \frac{P}{v} \tag{2.1}$$

where

H = Energy input, J/mm;
P = Total power of heat source, W; and
v = Travel velocity of heat source, millimeters per second (mm/s).

If the heat source is an arc, the energy input can be expressed to a first approximation, as follows:

$$H = \frac{VI}{v} \tag{2.2}$$

where

H = Energy input, J/mm;
V = Welding arc voltage, volts (V);
I = Welding arc current, amperes (A); and
v = Travel velocity of the heat source, mm/s.

Arc Efficiency

If the objective is to make a precise determination of the heat effects of the arc on the material being welded, the net energy input, H_{net}, should be used, as follows:

$$H_{net} = f_1 H = \frac{f_1 P}{v} = \frac{f_1 VI}{v} \tag{2.3}$$

where

H_{net} = Net energy input, J/mm;
f_1 = Heat transfer efficiency of the source (heat actually transferred to the workpiece divided by the total heat generated by the heat source);
H = Energy input, J/mm;
P = Total power of heat source, W;
V = Welding arc voltage, V;
I = Welding arc current, A; and
v = Travel velocity of the heat source, mm/s.

For arcs, the heat transfer efficiency is often termed the *arc efficiency*. With most consumable electrode arcs (e.g., those used in gas metal arc welding or submerged arc welding), the difference between the energy input, H, and the net energy input, H_{net}, is minimal since the heat transfer efficiency, f_1, is typically 0.8 to 0.9. With nonconsumable electrode processes such as gas tungsten arc welding and plasma arc welding, the value of f_1 can be as low as 0.5, and the arc efficiency factor can be considered to permit a more accurate determination of the net energy input.

The measurement of heat transfer efficiencies requires the use of calorimetric methods to determine the amount of heat deposited in a workpiece with a particular welding process. Such methods provide arc (heat transfer) efficiencies for various arc processes, as shown in Figure 2.1. The results in Figure 2.1 are in general agreement with a wide variety of investigations that have been conducted on arc efficiency.

Melting Efficiency

The primary function performed by fusion welding heat sources is to melt metal. The quantity of metal that must be melted to produce a certain length of weld is dictated by the thickness of materials being welded and the welding process. Almost without exception, it is preferable for metallurgical reasons to (1) melt the minimum amount of material and (2) melt the material with the minimum energy input. These objectives are easier to accomplish with higher energy density heat sources.

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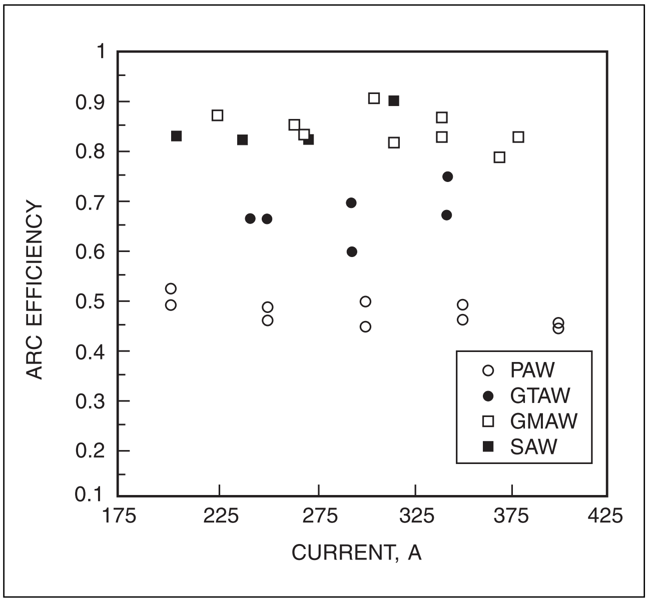


Source: DuPont, J. N., and A. R. Marder, 1995, Thermal Efficiency of Arc Welding Processes, *Welding Journal* 74(12): 406-s–416-s, Figure 3.

Figure 2.1—Arc Efficiencies as a Function of Welding Current for Different Arc Welding Processes

The term *melting efficiency* denotes the fraction of the net energy input (H_{net}) that actually melts metal. Whereas the heat transfer efficiency, f_1, is purely a heat source characteristic, the melting efficiency is a characteristic of both the heat source and the process of heat transfer in the materials being joined. The melting efficiency under a given welding condition can be determined from postweld knowledge of the area of the weld, the material welded, and the net energy input.

Figure 2.2 identifies three characteristic areas of a weld deposit—the base metal, the weld metal, and the heat-affected zone—of a cross section of a bead-on-plate weld.

The cross-sectional area of the weld metal, A_w, is given by the following equation:

$$A_w = A_m + A_r \tag{2.4}$$

where

A_w = Cross-sectional area of the weld metal, mm^2;
A_m = Cross-sectional area of the base metal that was melted; mm^2; and
A_r = Cross-sectional area of the added filler metal, mm^2. This area is sometimes referred to as *reinforcement*.

If no filler metal is added, then A_w equals A_m.

A specific theoretical quantity of heat is required to melt a given volume of metal (from ambient temperature). This theoretical quantity of heat is a property of the metal or alloy known as the *melting enthalpy*, Q. It is obtained by adding (1) the heat required to elevate the temperature of the solid metal to its melting point to (2) the heat required to convert a solid to liquid at the melting point (the heat of fusion). The following is a reasonable approximation of Q:

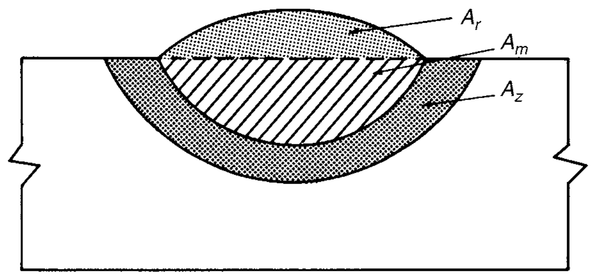
$$Q = \frac{(T_m + 273)^2}{300\,000} \tag{2.5}$$

where

Q = Melting enthalpy, joules per cubic millimeter (J/mm^3); and
T_m = Melting temperature of the metal, degrees Celsius (°C).

For steel, Q is calculated to be approximately 10.5 J/mm^3.

The melting efficiency, f_2, characterizing a weld pass is defined as the theoretical quantity of heat required to melt the weld deposit per unit length divided by the net energy input. This is expressed as follows:



Key:
A_m = Cross-sectional area of the melted base metal, mm^2
A_r = Cross-sectional area of the added filler metal, mm^2
A_z = Cross-sectional area of the heat-affected zone, mm^2

Figure 2.2—Weld Cross Section

$$f_2 = \frac{QA_w}{H_{net}} = \frac{QA_w v}{f_1 P} \tag{2.6}$$

where

f_2 = Melting efficiency;
Q = Melting enthalpy, J/mm^3;
A_w = Area of the cross section of weld metal, mm^2;
v = Travel velocity of heat source, mm/s;
H_{net} = Net energy input, J/mm;
f_1 = Heat transfer efficiency; and
P = Total power of heat source, W.

For an arc, the melting efficiency is as follows:

$$f_2 = \frac{QA_w v}{f_1 VI} \tag{2.7}$$

where

f_2 = Melting efficiency;
Q = Melting enthalpy, J/mm^3;
A_w = Cross-sectional area of weld metal, mm^2;
v = Travel velocity of heat source, mm/s;
f_1 = Heat transfer efficiency;
V = Welding arc voltage, V; and
I = Welding arc current, A.

The melting efficiency for a weld made under a known set of conditions can be determined following welding using the above equations, knowing the melting enthalpy of the metal welded, Q, the cross-sectional area of the weld, A_w, the energy input, H, and the heat transfer efficiency, f_1.

To predict the melting efficiency, the equations for two-dimensional heat flow in a thin plate have been solved to provide the analytical expression for estimating the melting efficiency, as follows:[4]

$$f_2 = \frac{1}{\left(\dfrac{8\alpha}{5vw}\right)+2} \tag{2.8}$$

where

f_2 = Melting efficiency;
α = Base metal thermal diffusivity, mm²/s;
v = Travel velocity of the heat source, mm/s; and
w = Weld width, mm.

A similar relation has been developed for three-dimensional heat flow conditions,[5] where the weld penetrates a relatively small fraction of the base metal thickness. It follows that

$$f_2 = \frac{1}{1.35\left(1+\left(1+\dfrac{10.4\alpha^2}{(vw)^2}\right)^{1/2}\right)} \tag{2.9}$$

where

f_2 = Melting efficiency;
α = Base metal thermal diffusivity, mm²/s;
v = Travel velocity of the heat source, mm/s; and
w = Weld width, mm.

These relations are useful because they show that the melting efficiency increases with increasing welding speed. They also predict that the melting efficiency cannot be higher than 0.50 for two-dimensional heat flow conditions and 0.37 for three-dimensional heat flow conditions. They show that the melting efficiency is maximized when the ratio of thermal diffusivity to the travel speed is low. In addition, the relations reveal the effect of thermal diffusivity. Higher base metal thermal diffusivities promote lower melting efficiencies since heat is conducted away from the fusion zone more quickly.

The effect of the thickness of the base metal is demonstrated by the differences between Equations (2.8) and (2.9). At equivalent travel speeds and thermal diffusivities, the melting efficiency is always higher for thin plates that result in two-dimensional heat flow conditions (see Equation [2.8]) as compared to thick plates that promote three-dimensional heat flow conditions (see Equation [2.9]).

In terms of welding process parameter effects, these equations show that travel speed governs the melting efficiency. Experimentally determined melting efficiencies as a function of travel speed are shown in Figure 2.3 for several arc processes. For these arc processes, the melting efficiencies approach 0.5 (i.e., 50% of the heat that enters the material results in melting). This is consistent with the maximum melting efficiency predicted from Equation (2.8), which approaches 0.5 as v increases.

The sensitivity of melting efficiency to the travel speed can be seen from the results presented in Figure 2.4, which shows two different arc welds made with the same process at the same energy input, but at different travel speeds. The significantly higher melting efficiency achieved with the faster travel speed is obvious from the much greater area of base metal melted. The parameters illustrated in Figure 2.4(A) are P = 3823 W; v = 10 mm/s; and H = 383 J/mm. In Figure 2.4(B), P = 10170 W; v = 26 mm/s; and H = 391 J/mm.

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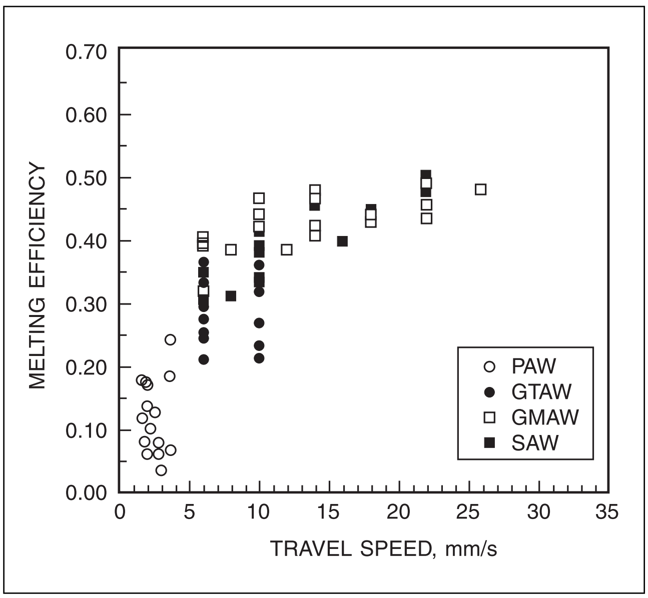

Source: DuPont, J. N., and A. R. Marder, 1995, Thermal Efficiency of Arc Welding Processes, *Welding Journal* 74(12): 406-s–416-s, Figure 9.

Figure 2.3—Melting Efficiency

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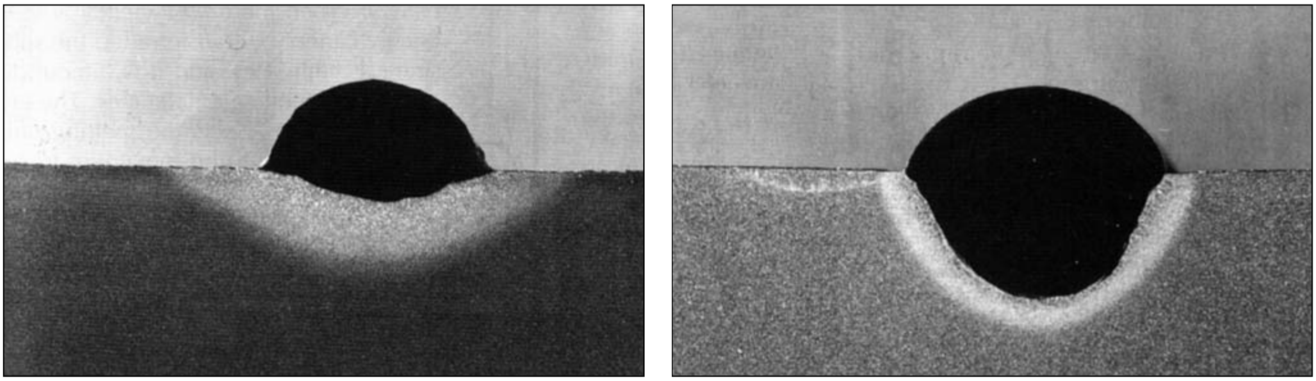
5. Okada, A., 1977, Application of Welding Efficiency and its Problems, *Journal of the Japanese Welding Society* 46(2): 53–61.



(A)

(B)

Source: DuPont, J. N., and A. R. Marder, 1995, Thermal Efficiency of Arc Welding Processes, *Welding Journal* 74(12): 406-s–416-s, Figure 13.

Figure 2.4—Weld Cross Sections Produced at Different Welding Speeds

SOLID-STATE WELDS

Solid-state welding (SSW) processes effect the coalescence of materials at temperatures below their melting points. Solid-state bonds can be produced by macroscopic or microscopic processes at the contacting surfaces of the materials to be joined. An energy source, usually mechanical, is utilized to create the macroscopic movement of material, often with the production of heat.

The solid-state processes all involve some type of mechanical movement that produces the energy required for welding. The production of friction between adjoining surfaces by means of mechanical action is a common means of developing the movement and heat necessary to accomplish joining. Friction welding (FRW) and a variation, inertia friction welding (IFW), use this method to produce coalescence.

Movement and heating by means of friction or impact contribute significantly to joining for processes such as ultrasonic welding (USW) and explosion welding (EXW). Cold welding (CW) is a unique process that accomplishes joining through the development of slow plastic deformation between the surfaces being joined without a significant generation of heat. These processes are discussed below in the section "Energy Sources for Welding."

Solid-state welds can also be produced by microscopic mechanisms that rely on atomic diffusion between materials at their contacting surfaces. The diffusion welding (DFW) process relies on these phenomena. Elevated temperatures and contact pressure are typically required to accelerate the diffusion process. The elevated temperatures are usually provided by some sort of furnace operated with an electrical or chemical energy source. However, the source of the heat is not intimately associated with the physics of the process that forms the weld. Diffusion welding is discussed in the section "Energy Sources for Welding."

ENERGY SOURCES FOR WELDING

All welding processes require some form of energy. For many processes, the energy source provides the heat necessary for welding and joining. Although various joining processes utilize no heat, they nevertheless require some form of energy to produce a bond. The energy sources for the welding processes discussed in this section are grouped into five categories: electrical sources, chemical sources, focused sources, mechanical sources, and solid-state sources.

ELECTRICAL SOURCES

Among the many welding processes that use electrical sources are arc welding, resistance welding, and electroslag welding. According to *Standard Welding Terms and Definitions*, AWS A3.0:2001, eighteen welding processes and their variations use an electric arc as the source of heat to accomplish fusion.[6] In the resistance welding processes, heat and pressure are used to produce welds. Electroslag welding utilizes the resistance of a wire electrode to the flow of current in an electrically conductive bath of molten slag to produce heat for welding.

Arc Welding

The electric arc is widely used in welding processes because the heat of the arc can be effectively concentrated and controlled.[7] An electric arc consists of a relatively high current discharge sustained through a thermally ionized gaseous channel termed a *plasma column*. The arc is established between a welding electrode and the workpiece. The electrode may be nonconsumable, as for gas tungsten arc welding and plasma arc welding, or it may be consumable and provide filler metal, as for shielded metal arc welding, gas metal arc welding, and submerged arc welding. In the case of consumable electrodes that provide filler metal, the heat input to the electrode is carried to the weld in the form of thermal energy of the liquid filler metal.

The power of an arc may be expressed in electrical units as the product of the current passing through the arc and the voltage drop across the arc. Given the typical values of 300 A and 25 V for current and voltage, respectively, 7500 W of electrical power are dissipated as heat. However, as described in the previous section, not all the heat generated in the arc can be effectively utilized in arc welding processes. Convection, conduction, radiation, and spatter are responsible for heat losses that typically result in heat transfer (arc) efficiencies of from 0.5 to 0.9. A typical welding arc contacts the workpiece over an area that can be estimated as 10 mm^2. An arc efficiency of 0.8 and the figures above would yield a typical arc energy density in the range of 750 W/mm^2.

In plasma arc heating sources, the arc is forced through a nozzle to constrict its diameter. Because a higher voltage is required to drive the arc through the nozzle and because the constriction reduces the diameter of the arc cylinder, the temperature of the arc and the energy density are significantly greater than those available with other nonconsumable electrode welding processes. The arc exits from the nozzle in the form of a high-velocity, intensely hot columnar plasma jet. This plasma jet is referred to as a *plasma arc* and can be operated as either a transferred or a nontransferred arc.[8]

Due to its high energy density, the plasma arc is effectively utilized for cutting as well as welding. The plasma arc cutting of 25 mm aluminum plate at a speed of 20 mm/s utilizes a transferred arc. A typical operation might require an arc using 170 V and 400 A with a gas flow of 70 liters per minute (L/min) through a nozzle 3 mm in diameter. The 68 kilowatts (kW) of power would produce a power density in the nozzle of approximately 8500 W/mm^2 and an average gas temperature of 9700°C to 14 700°C. The resulting gas velocity approaches sonic velocity at these high temperatures. For plasma arc welding operations, a lower gas velocity is used to avoid loss of the molten weld pool, resulting in welding rather than cutting.

Resistance Welding

Resistance welding processes employ a combination of pressure and heat to produce a weld between the workpieces.[9] Resistance heating occurs as electrical welding current flows through the workpieces. The workpieces are generally in the secondary circuit of a transformer. The transformer converts high-voltage, low-current commercial power into suitable high-current, low-voltage welding power.

The heat generated by the current flow may be expressed as follows:

$$E = I^2Rt \tag{2.10}$$

where

E = Heat generated, J;[10]
I = Current, A;
R = Resistance, ohms (Ω); and
t = Duration of current flow, s.

The welding current and time can be easily measured, but the measurement of resistance is complex and difficult. The resistance that is important in

6. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society.
7. For a general discussion of the arc welding processes, refer to Chapter 1 of this volume. For information on arc welding power sources, refer to Chapter 1 in O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

8. For an explanation of transferred and nontransferred arcs, refer to the discussion of plasma arc welding in Chapter 1 of this volume and Chapter 2 in O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.
9. For a general discussion of resistance welding, refer to Chapter 1 of this volume.
10. Variable E in this equation is measured in units of energy, e.g., joules, and should not be confused with variable H, used for energy input, and measured in units of energy per unit length, e.g., J/mm. The concept of energy per unit length is not applicable to a process that uses a stationary energy source, as is typical of resistance welding, in which total energy is more meaningful.

resistance spot welding is composed of the following factors:

1. Contact resistance between the electrodes and the work,
2. Contact resistance between the workpieces,
3. Body resistance of the workpieces, and
4. Resistance of the electrodes.

Contact resistance is greatly affected by surface conditions, such as cleanliness and the absence of oxides or other chemical compounds, and by the smoothness of the surface. In addition, contact resistance is directly related to the resistivities of the materials in contact and inversely related to the pressure on the contact area. When the workpieces have uniform surface conditions, welding pressure becomes the major factor in determining contact resistance. Nonuniform surface oxides, such as mill scale on steel, make it difficult to maintain the uniform control of energy in resistance welding. It is therefore preferable to remove these oxides chemically or mechanically prior to welding.

The resistance of the base metal is proportional to the resistivity of the material and the length of the current path and is inversely proportional to the area of the current path. For materials of high resistivity and heavier gauges, the base metal resistance becomes more important, and the contact resistance becomes less important. For high-conductivity materials, contact resistance is the most important factor. Differences in contact resistance are reflected in the rather widely differing currents that are required to make the same size weld in various materials.

In general, the magnitudes of the contact resistances between two faying surfaces of uncoated steel are approximately 100 micro-ohms (μΩ). As a result, the currents are high, running into the thousands and tens of thousands of amperes. In the case of capacitor-discharge power sources, the current may be as high as several thousand amperes, but the weld time is short.

The contact resistance between steel workpieces, for example, largely disappears during the first half-cycle of alternating-current (ac) flow. However, heat generated at the contacting surfaces during the first cycle raises the temperature of the base metal and causes a significant increase in base metal resistance, which rises with temperature.[11] The increase in base metal resistance makes the welding current more effective in producing a weld. The importance of contact resistance in materials of medium resistivity, such as steel, is borne out of the fact that higher welding forces, which reduce contact resistance, require higher welding currents.

11. The electrical resistance of most metals increases significantly with increasing temperature.

The quantity of energy required to produce a given resistance weld is determined by several factors. Keys factors are the weld area (heated volume), the peak temperature, the specific heat of the workpieces, and the heat loss into the surrounding metal and electrodes. An increase in magnitude of one or more of these factors requires a corresponding increase in energy to produce the weld.

The particular resistance welding process and the welding schedule selected also significantly affect the energy factors listed above. For example, heat loss becomes significantly greater as the duration of the current flow increases. Hence, long weld times require a corresponding increase in input energy to the weld to compensate for the heat loss.

To illustrate, consider resistance spot welding utilizing a conventional step-down transformer power source. Using Equation (2.10), it is possible to estimate the heat generated, E, in the spot welding of two sheets of 1.0 mm thick steel that require a current of 10 000 A for 0.1 second. If an effective resistance of 100 μΩ is assumed, Equation (2.9) results in the following:

$$E = (10\ 000)^2(0.0001)(0.1) = 1000 \text{ J} \tag{2.11}$$

where E denotes heat generated in joules.

Approximately 10.5 J are required to heat and melt 1 mm^3 of steel [see Equation (2.5)]. Assuming that the fusion zone for the weld is a cylinder 5 mm in diameter and 1.5 mm in height, the fused metal would have a volume of approximately 29 mm^3, requiring approximately 305 J to melt. The remaining heat (1000 J – 305 J = 695 J) would be absorbed by the surrounding metal. A melting efficiency of 0.31 results for these conditions. Also, the instantaneous power can be calculated to be 1000 J/0.1 s = 10 000 W. Using the assumed weld area as the electrode contact area, an energy density of 10 000 $W/[\pi\ (5\ mm/2)^2] \cong 500\ W/mm^2$ can be estimated. This energy density is comparable to the typical value for arc welding as estimated in the previous section.

In comparison, consider the use of a capacitor-discharge power supply in making a projection weld between two sheets of steel 1 mm in thickness. A weld current pulse of 30 000 A and a weld time of 0.005 s would be typical. In this case,

$$E = (30\ 000)^2(0.0001)(0.005) = 450 \text{ J} \tag{2.12}$$

where E denotes heat generated in joules.

In this instance, the lesser quantity of heat is a result of a lower heat loss and the concentration of heat at the weld interface as a result of the faster weld time.

Electroslag Welding

In electroslag welding,[12] an electrode wire is fed through an electrically conductive bath of molten slag. The resistance of the slag bath to the flow of current produces heat, the bulk of which is concentrated primarily in the slag area immediately surrounding the tip of the electrode. The quantity of heat generated, *E*, in the slag pool can be expressed as follows:

$$E = VIt \tag{2.13}$$

where

E = Heat generated (in the slag pool), J;
V = Voltage, V;
I = Welding current, A; and
t = Time, s.

This heat melts the wire and the base metal to form the weld. As the electrode wire or consumable nozzle and wire melt, the weld metal is deposited through the molten slag that dissolves some impurities and protects the weld metal from the atmosphere. The weld metal then solidifies upward as heat is extracted by the surrounding base metal and the shoes or dams that contain the molten flux and metal.

The heat transfer efficiency achieved in electroslag welding is quite high. However, because the heat is transferred to the base plates over a relatively large area, the energy density is low (typically 10 W/mm^2 to 50 W/mm^2) when compared to arc processes. Due to the low energy density, the melting efficiency is also low, typically on the order of 20%.

CHEMICAL SOURCES

Chemical energy stored in a wide variety of forms can be converted to useful heat. The temperature and the rate of reaction are two major characteristics that determine the application of the various energy sources. Oxyfuel gas welding and thermite welding are examples of processes that use chemical heat sources.

Oxyfuel Gas Welding

Chemical energy stored in combustible gases can be converted to useful heat. As stated above, the temperature and the rate of reaction are major characteristics that determine the effectiveness of chemical heat sources.

The oxyfuel gas welding of steel requires the following flame characteristics: (1) a high flame temperature capable of melting and controlling the weld metal and (2) a neutral or reducing atmosphere surrounding the molten metal to minimize contamination before solidification.

Most of the commonly used fuel gases achieve maximum flame temperatures of over 2760°C when mixed with oxygen and burned in an open flame. At maximum temperature, the flame is oxidizing in nature and therefore unsuited for welding due to the formation of oxides in the weld metal. Adjusting the flame to neutral lowers the flame temperature, as shown in Table 2.1.

With the exception of the oxyacetylene flame, the flame temperature is reduced to the point at which it is difficult to control the weld pool in materials other than thin sheet metal. Methylacetylene-propadiene gas (stabilized) can be used for welding, provided that two special procedures are followed. First, the fuel-to-oxygen ratio must be adjusted to be slightly oxidizing so that the flame temperature is moderately increased. Second, a highly deoxidized filler metal must be used.

The combustion of acetylene in oxygen at the orifice of a torch takes place in two steps. The first step is the burning of carbon to carbon monoxide, in which the hydrogen remains unconsumed. This burning takes place in a small bluish-white cone close to the torch in which the gases are mixed. This reaction provides the heat that is most effective for welding. In the second step, the conversions of carbon monoxide to carbon dioxide and that of the hydrogen to water vapor take place in a large blue flame that surrounds the welding operation but contributes only a preheating effect. The chemical reactions representing these two steps of combustion are expressed as follows:

$$C_2H_2 + O_2 \rightarrow 2CO + H_2$$
$$2CO + H_2 + 1.5O_2 \rightarrow 2CO_2 + H_2O$$

Table 2.1
Flame Temperatures of Oxyfuel Gases

Gas	Maximum Temperature, °C	Neutral Flame Temperature, °C
Acetylene	3100	3100
Methylacetylene-propadiene (stabilized)	2900	2600
Propylene	2860	2500
Hydrogen	2870	2390
Propane	2780	2450
Natural gas/methane	2740	2350

12. For a general discussion of electroslag welding, refer to Chapter 1 of this volume and Chapter 8 in O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook*, Miami: American Welding Society.

The first reaction generates heat by the breaking up of acetylene as well as by the formation of carbon monoxide. The dissociation of acetylene liberates 227 kilojoule per mole (kJ/mol) at 15°C. The combustion of carbon to form carbon monoxide liberates 221 kJ/mol. The total heat supplied by the first reaction is therefore 448 kJ/mol of acetylene.

The second reaction liberates 242 kJ/mol of water vapor by the burning of hydrogen. The combustion of carbon monoxide provides 285 kJ/mol or an additional 570 kJ/mol for the reaction. The total heat supplied by the second reaction is therefore 812 kJ/mol.

The total heat supplied by the two reactions is 1260 kJ/mol of acetylene. The concentrated heat liberated by the first reaction in the small inner cone of the flame is 35.6% of the total heat. The remaining heat is developed in the large brush-like outer envelope of the flame, and is effective for preheating. It is this heat that reduces the thermal gradient and cooling rate for oxyacetylene welding (OAW).

One volume of oxygen is used in the first step of the combustion to burn one volume of acetylene. This oxygen must be supplied in the pure state through the torch. The 1.5 volumes of oxygen required in the second step are supplied from the atmosphere. When exactly enough oxygen is supplied to burn the carbon to carbon monoxide, as indicated in the first step, the resulting flame is said to be *neutral*. If less than enough oxygen is supplied to complete the combustion of the carbon, the flame is said to be a *reducing* or an *excess acetylene flame*. If more than enough oxygen is supplied for the first reaction, a so-called *oxidizing flame* is produced.

Medium-sized oxyacetylene torches are equipped with a variety of orifices to accommodate acetylene flow rates from 0.9 L/min to 142 L/min. At a flow rate of 28 L/min, the total heat available would be 25 kJ/s. However, as previously stated, approximately one-third of the heat is liberated in the small inner core of the flame. Therefore, only 8.8 kJ/s are available at the torch tip. The efficiency of heat utilization is very low in most cases. Typically, heat transfer rates for oxyacetylene torches are on the order of 1.6 J/mm^2/s to 16 J/mm^2/s. This can also be expressed as 16 W/mm^2 and compared to the typical energy density for arc welding as presented in Equations (2.8) and (2.9) to observe that it is a factor of 10 to 100 lower.

In oxyhydrogen welding (OHW), the combustion of hydrogen is a simple reaction with oxygen to form water vapor. If sufficient pure oxygen is supplied to burn all of the hydrogen, the flame temperature would be approximately 2870°C. However, this would not provide a protective outer envelope of reducing atmosphere to shield the weld pool. If only enough pure oxygen to burn half of the hydrogen is provided, the concentrated heat would be 121 kJ/mol. In the latter case, the flame temperature would drop to a little over 2480°C.

Thermite Welding

Thermite welding (TW)[13] is a process that uses heat from exothermic reactions to produce coalescence between metals. The process name is a generic term denoting reactions between metal oxides and reducing agents. Thermite mixtures consist of oxides with low heats of formation and metallic reducing agents that have high heats of formation when oxidized. The excess heats of formation of the reaction products provide the energy source required to form the weld.

If finely divided metal oxides and aluminum are blended and ignited by means of an external heat source, the aluminothermic reaction will occur according to the following chemical reaction:

Metal oxide + aluminum → aluminum oxide + metal + heat

The most common thermite welds and the respective heat of reactions, E, are as follows:

$$3/4Fe_3O_4 + 2Al \rightarrow 9/4Fe + Al_2O_3 \quad (E = 838\ kJ) \quad (1)$$
$$3FeO + 2Al \rightarrow 3Fe + Al_2O_3 \quad (E = 880\ kJ) \quad (2)$$
$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 \quad (E = 860\ kJ) \quad (3)$$
$$3CuO + 2Al \rightarrow 3\ Cu + Al_2O_3 \quad (E = 1210\ kJ) \quad (4)$$
$$3\ CU_2O + 2Al \rightarrow 6Cu + Al_2O_3 \quad (E = 1060\ kJ) \quad (5)$$

The first reaction represents the most common method for the thermite welding of steel and cast iron parts. Reactions (4) and (5) are commonly used for joining copper, brasses, bronzes, and copper alloys to steel.

In thermite welding, the workpieces to be welded are aligned, leaving a gap between them. Then, a mold is built (either on the workpieces or formed on a pattern of the workpieces) and placed in position. The next step varies according to the size of the workpieces. If they are large, preheating within the mold cavity is necessary to bring the parts to welding temperature and to dry out the mold. If they are small, however, preheating is often eliminated. Next, the superheated products of a thermite reaction flow into the gap between the workpieces with sufficient heat to melt both faces of the base metal. When the filler metal has cooled, all unwanted excess metal is removed by oxygen cutting, machining, or grinding.

13. The term *thermite welding* is listed as a standard term in American Welding Society Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society (see Appendix A of this volume). This process is discussed in more detail in O'Brien, R. L., ed., 1991, *Welding Processes*, Vol. 2 of *Welding Handbook*, 8th ed., Miami: American Welding Society, where it is referred to as *Thermit*™ *welding*.

The maximum temperature that can be obtained from such a reaction can only be estimated. The theoretical maximum temperature of the reaction is approximately 3200°C. In practice, the temperature varies between 2200°C and 2400°C.

Thermite reactions are nonexplosive. The ignition temperature for thermite granules suitable for welding is in the area of 1200°C. Therefore, a thermite mixture does not constitute a fire hazard, nor does it require special storage conditions as long as it is not in the proximity of an open heat source (e.g., flame or fire). To start the reaction, a special starting powder or rod is required. The starting mixture incorporates peroxides, chlorates, or chromates as the oxidizing agent.

FOCUSED SOURCES

Two sources of welding energy, the laser beam and the electron beam, are focused sources that are governed by the laws of optics. The laser beam produces coalescence in a weldment with the heat from a laser beam impinging on the joint. In the electron beam welding process, coalescence is achieved with the heat from a concentrated beam, composed primarily of high-velocity electrons, impinging on the joint. Both energy sources are widely used in welding and cutting applications.

Laser Beam Welding

In laser beam welding (LBW), the laser beam is focused by various arrangements of lenses and mirrors. Due to the small focal spot sizes that can be obtained, high power densities can be produced. The high power densities achievable with laser beams cause the intense evaporation of metal. Recoil forces associated with the evolution of vapor from the surface of the material produce a needle-like, vapor-filled cavity or keyhole in the workpiece through which the beam can penetrate. The molten metal flows from the front to the rear of the keyhole, where it solidifies to form a weld with a very high ratio of depth to width.

The high degree of spectral purity and the low divergence of laser radiation permit a laser beam to be focused on extremely precise areas, resulting in power densities often greater than 10 kW/mm^2. This is an order of magnitude higher than that achievable with welding arcs. The unfocused beam from a laser source is typically 1 mm to 50 mm in diameter; it must therefore be focused to be useful for laser beam welding applications. The focused spot size of a laser beam, d, is expressed as follows:

$$d = \frac{M^2 4\lambda f}{1000\pi D} \tag{2.14}$$

where

d = Focused spot size, mm;
M^2 = Beam quality factor;
λ = Wavelength of laser radiation, µm;
f = Focal length of the focusing lens, mm;
π = 3.1416; and
D = Beam diameter at focus lens, mm.

The average power (energy) density, PD, at the focal plane of the lens can be estimated by using the following equation:

$$PD = \frac{P}{\left(\frac{\pi d^2}{4}\right)} \tag{2.15}$$

where

PD = Power density, W/mm^2;
P = Input beam power, W;
π = 3.1416; and
d = Focused spot size, mm.

Combining Equations (2.14) and (2.15) shows the manner in which the power density *(PD)* at the focal plane of the laser (workpiece) depends on the properties of the laser and the focusing system, as follows:

$$PD = \frac{\pi P}{4}\left(\frac{1000D}{M^2\lambda f}\right)^2 \tag{2.16}$$

where

PD = Power density, W/mm^2;
P = Input beam power, W;
D = Beam diameter at focus lens, mm;
π = 3.1416;
M^2 = Beam quality factor;
f = Focal length of the focusing lens, mm; and
λ = Wavelength of laser radiation, µm.

Carbon dioxide and Nd:YAG lasers are the lasers most commonly used for welding. Carbon dioxide lasers use a mixture of nitrogen, helium, and carbon dioxide gases. They produce a beam with a wavelength of 10.6 µm and beam quality factors (M^2) ranging from 1 to approximately 10 and can be operated with continuous wave output or pulsed at several thousand pulses per second. In the Nd:YAG laser, the lasing medium is a single crystal of yttrium-aluminum-garnet (YAG) doped with a small concentration of neodymium, a rare earth element.[14] These lasers produce radiation having a wavelength of 1.06 μm and M^2 varying over an extremely wide range—from approximately 1 for low power lasers to around 200. They can be operated with continuous wave output or pulsed at rates up to one thousand pulses per second. As laser beams are minimally affected by passage through the atmosphere, they do not require operation in a vacuum as is typical of electron beams.

Most metallic surfaces reflect appreciable amounts of incident laser radiation. In practice, however, sufficient energy is usually absorbed to initiate and sustain a continuous molten pool. Nd:YAG and carbon dioxide lasers are capable of producing high-speed, highly efficient continuous metal welds in keyhole mode. Nd:YAG lasers of 500 W output are capable of welding steel sheet 1 mm thick at several millimeters per second. Carbon dioxide lasers of 20 kW continuous wave output power can produce deep penetration welds in 13 mm thick steel at 25 mm/s.

In steel, if the power density is not high enough for keyholing to occur (less than approximately 5 kW/mm^2), a relatively shallow weld having an approximate hemispherical cross section and resembling a gas tungsten arc weld will be produced. This so-called *conduction-mode* welding has poor efficiency and is usually used only for thin materials.

Electron Beam Welding

Electron beam welding (EBW) is similar to laser welding except that electrostatic and magnetic lenses focus a beam of electrons. In electron beam welding, energy is developed in the workpiece by bombarding it with a focused beam of high-velocity electrons. The total power (energy) density at the workpiece surface is expressed as follows:

$$PD = \frac{neV}{A} = \frac{VI}{A} \qquad (2.17)$$

where

- PD = Power density, W/mm^2;
- n = Total number of electrons per second in the beam;
- e = Charge on an individual electron, 1.6×10^{-19} coulomb;
- V = Accelerating voltage on the electrons, V;
- I = Beam current, A; and
- A = Area of the focused beam at the workpiece surface, mm^2.

14. Lasers in which single crystals of yttrium-aluminum-garnet or glass doped with neodymium ions are abbreviated as Nd:YAG and Nd-glass, respectively.

The depth of penetration of a focused beam is determined by the power density at the work surface and the speed of welding. Electron beams are most effective in a vacuum, where they are not scattered or dispersed by collision with gas molecules.

Power (energy) densities of 1 kW/mm^2 to 100 kW/mm^2 are routinely achieved, and 10 MW/mm^2 can be obtained with electron beams. This is well in excess of power densities achievable with laser beams. Electron beam welding is generally performed at voltages between 20 kV and 150 kV.

Three commercial variants of the electron beam welding process are used, distinguished by the degree of vacuum utilized. These are as follows:

1. High vacuum EBW, the pioneering process that operates at a pressure of 0.1 pascal (Pa) or lower;
2. Medium or soft vacuum EBW, which operates at pressures of 10.0 Pa; and
3. Nonvacuum EBW, which operates at 100 kilopascal (kPa).

Each variation has different performance capabilities and excels in different application areas. The penetration capability is inversely related to the pressure because higher pressures produce increased scattering of the beam electrons due to collisions with gas atoms. Scattering spreads the beam and reduces the energy density at the workpiece.

The advantages associated with the electron beam welding process include a high depth-to-width ratio; high strength; and the ability to weld thick sections in a single pass with relatively low heat input, low distortion, and a narrow heat-affected zone. These advantages are the result of the high power (energy) density.

MECHANICAL SOURCES (SOLID-STATE)

Three welding processes—friction welding, ultrasonic welding, and explosion welding—use mechanical sources of energy. These are classified as solid-state processes because no melting of the base metals occurs. These processes all involve some type of mechanical movement that produces the energy for welding. This feature distinguishes these three from other solid-state processes (e.g., diffusion welding), which are characterized by atomic motion.

Friction Welding

In friction welding (FRW), a bond is created between a stationary workpiece and a rotating workpiece by generating frictional heat between them while they are subjected to high compressive forces on the contacting surfaces. Application of this process requires that the rotating workpiece be essentially symmetrical about the axis of rotation, while the other can be of any suitable geometry that is within the clamping limitations of the welding machine.

In practical application, this welding heat source utilizes one of the following three approaches: (1) relatively slow rotational speeds and high force, (2) high speed and relatively low force, or (3) a flywheel that is disengaged from the rotating drive before the start of welding. In the latter case, the rotational speed continuously decreases during the welding cycle. The first two approaches are referred to as conventional friction welding, while the latter variation is termed *inertia friction welding* (IFW) because a flywheel provides the energy. Both make use of the frictional heating of the faying surfaces to accomplish welding.

Because frictional heat is related to speed and force, the time required to produce a bond is a function of both of these variables. Also, the radial temperature distribution is not uniform. It is highest near the outer surface where the surface speed is highest.

The average interface temperature is always below the melting point of either workpiece being joined. Thus, the metallurgical bond is achieved by diffusion rather than by fusion. Consequently, the process is admirably suited for joining dissimilar metals, particularly those that undergo undesirable phases when joined by fusion processes. The width of the diffusion zone may vary from being so thin that it cannot accurately be defined in width with present techniques to a width that is readily detected by low-power magnification.

Ultrasonic Welding

Ultrasonic welding (USW) is generally used to produce spot, straight, and circular seam (ring) welds between workpieces, at least one of which is of sheet or foil thickness. Ultrasonic welds are produced by introducing high-frequency vibratory energy into the weld zone of the metals to be joined. The workpieces are clamped together between two tips or jaws, and the vibratory energy is transmitted through one or both sonotrode tips that oscillate in a plane essentially parallel to the weld interface. This oscillating shear stress results in elastic hysteresis, localized slip, and plastic deformation at the contacting surface, reactions that disrupt surface films and permit metal-to-metal contact. Ultrasonic welding thus produces a metallurgical bond between similar or dissimilar metals without melting. The elastic and plastic deformations induce a very localized, transient temperature rise at the weld interface. Under the proper conditions of clamping force and vibratory power, the temperatures reached are typically in the range of 35% to 50% of the absolute melting point of the metals being joined.

By means of a frequency converter, 60 Hz of electrical power is transformed into high-frequency power, generally within the range of 15 000 Hz to 75 000 Hz, although higher or lower frequencies may be used. The high-frequency electrical power is converted into acoustical power at the same frequency by one or more transducers of either the magnetostrictive or piezoelectric ceramic types. Appropriate acoustical coupling members transmit the acoustical power from the transducer to the sonotrode tip and into the workpieces.

With recently developed solid-state frequency converters, more than 90% of the line power is delivered electrically as high-frequency power to the transducer. The electromechanical conversion efficiency of the transducer, that is, its efficiency in converting electrical power into acoustical power, is in the range of 25% to 35% for magnetostrictive nickel-stack transducers and is frequently in excess of 75% for piezoelectric transducers such as lead-zirconate-titanate ceramics. Thus, in the case of ceramic transducers, as much as 65% to 70% of the input electrical line power can be delivered to the weld metal as acoustical power.

The amount of acoustical energy required to weld a given material increases with material hardness and thickness. This relationship for ultrasonic spot welding can be expressed, as a first approximation, by the following equation:

$$E = K_1(H_n t)^{3/2} \tag{2.18}$$

where

E = Acoustical energy, J;
K_1 = 8000 J/mm$^{3/2}$;
H_n = Vickers microindentation hardness number; and
t = Thickness of the material adjacent to the ultrasonically active tip, mm.

This empirical equation is reasonably valid for common metals such as aluminum, steel, nickel, and copper in thicknesses up to at least 0.80 mm. Some of the more exotic materials are less responsive to this relationship. Experimentation over a range of welding machine settings is usually recommended to establish precise settings that will produce satisfactory welds in a given material and material thickness.

Explosion Welding

In explosion welding (EXW), the detonation of an explosive is utilized to accelerate a component (termed the *flyer*) to a high velocity as it collides with a stationary component. At the moment of impact, the kinetic energy of the flyer plate is released as a compressive stress wave on the surfaces of the two components. During explosive welding, the collision progresses across the surface of the plates being welded, forming an angle between the two colliding components. The surface films are liquefied, scarfed off the colliding surfaces, and jetted out of the interface, leaving perfectly clean, oxide-free surfaces. Under these conditions, the compressive interatomic and intermolecular forces create a bond. The result of this process is a weld without a heat-affected zone.

An explosive provides the energy for the explosion process. The detonation velocity of the explosive must fall within limits to produce the necessary impact velocity and angle between the two components. The maximum velocity of the explosive detonation should not exceed the highest sonic velocity within the materials being welded. The physical forms of the explosives utilized include plastic flexible sheet, cord, and pressed, cast, granulated, and liquid shapes. These explosives also vary in detonation velocity. They are usually detonated with a standard commercial blasting cap.

Most explosion welding applications utilize the detonation of a low-velocity explosive, which is usually placed in direct contact with the flyer plate. Low-velocity explosives develop relatively lower pressures than high-velocity explosives and can be used without causing shock damage. These explosives make it easier and more practical to achieve explosion welding. They should have a detonation velocity of approximately 2400 m/s to 3600 m/s. The detonation velocity depends on the thickness of the explosive layer and the packing density.

When the detonation velocity is lower than the sonic velocity of the metal, the pressure generated in the metal by the expanding gases moves faster than the detonation and is spread out ahead of the detonation front. A shock wave is not produced. However, if the detonation velocity of the explosive slightly exceeds the metal sonic velocity, a shock wave which moves slightly ahead of the detonation is formed. High-velocity explosives are difficult to use for high-quality welding because they can cause considerable shock wave damage that results in spalling along the edges and fissuring at the bond interface. When high-velocity explosives are used, thick buffers are required between the explosive and the cladding plate.

The velocity of the flyer plate can be changed by changing the explosive charge per unit of area. If it is increased, several of the following can happen:

1. Angle of incidence at which bond waviness begins to increase;
2. Larger waves are produced with the same angle of incidence;
3. Range of angles within which waves are produced increases; or
4. Tendency for the formation of intermetallic compounds in the weld interface increases.

Two components will not bond if the explosive charge per unit area is too low. Thus, a minimum flyer plate velocity must be achieved.

The detonation velocity tends to be constant throughout the entire explosion. Since the energy release of most explosives depends on the thickness of the explosive and the degree of confinement, the detonation velocity may vary as these parameters are changed. The velocity can also be modified by the selection of the explosive ingredients and by changing the packing density of the explosive.

SOLID-STATE SOURCES

Solid-state sources provide energy that drives the macroscopic or microscopic coalescence of materials in the solid state.

Diffusion Welding

Diffusion welding (DFW) is a solid-state welding process that relies almost solely on microscopic atomic diffusion to create a solid-state bond. The term *diffusion* describes the movement of atoms on a microscopic level in a solid, vaporous, or liquid material. As an example, in a room free of air currents, a fragrance released on one side of the room will travel throughout the room by means of diffusion. The atoms or molecules of the fragrance naturally diffuse from the location of high concentration (where it is released) to the areas of low or no concentration (remote from the release point).

Diffusion in metal systems is usually categorized as one of three physical mechanisms, depending on the path of the diffusing element. Each of these mechanisms—volume diffusion, grain-boundary diffusion, and surface diffusion—has a different diffusivity constant. The specific rates for grain boundary and surface diffusion are higher than the rate for volume diffusion.

Fick's first law gives the basic equation for diffusion in metals as follows:

$$\frac{dm}{dt} = -D\frac{\partial c}{\partial x}A \tag{2.19}$$

where

dm/dt = Flow rate of metal across a plane perpendicular to the direction of diffusion, g/s;

D = Diffusion coefficient whose values depend on the metallic system being considered, mm^2/s;

$\partial c/\partial x$ = Concentration gradient that exists at the plane in question, where c is expressed in g/mm^3); and

A = Area of the plane across which diffusion occurs, mm^2.

It should be noted that the diffusion coefficient, D, is not generally constant. It is a function of such dynamic variables as temperature, concentration, and crystal structure.

Several mechanisms can account for the diffusion of atoms in metals. Two of these are the interstitial mechanism and the vacancy mechanism. The interstitial mechanism is concerned with the movement of atoms having small atomic radii compared to the matrix atoms. These elements move from one location to another along the interstices of the crystal lattice, hence the term *interstitial elements*. These moves occur within the crystal without distorting or permanently displacing the matrix atoms.

The matrix or substitutional atoms use the vacancy mechanism for their mode of transportation. Because of their size, it is literally impossible for these atoms to migrate along the interstices. The only paths open to them are the vacancy sites. Although the energy required to move a matrix atom is equal to that required for an interstitial element, the rate is considerably slower because fewer vacant locations are available to the atoms.

The pronounced effect that temperature has on diffusion may be evaluated by the rule of thumb that holds that an 11°C rise in temperature will double the diffusion coefficient. It has been found that the diffusion coefficient changes with a variation in concentration. For example, the diffusion coefficient of carbon in iron at 930°C will undergo a three-fold increase over a range of carbon from 0% to 1.4%.

The crystal structure has also been found to influence the diffusion coefficient at a given temperature. The self-diffusion of iron takes place 100 times more rapidly in ferrite than in austenite. In addition, the directionality of a crystal influences the diffusion coefficient, and it has been demonstrated that the rate of diffusion is greater in cold-worked structures than in annealed structures.

A more accurate estimate of the effects of temperature on diffusion rate is provided by the Arrhenius equation, as follows:

$$D = D_0 \exp(-\frac{q}{RT}) \tag{2.20}$$

where

D = Diffusion coefficient, mm^2/s;

D_0 = Proportionality constant (the upper limit of the diffusion coefficient), mm^2/s;

q = Activation energy, kJ/mol;

R = Ideal gas constant, 8.3KJ/mol K; and

T = Absolute temperature, K.

The activation energy is a measure of the energy barrier that must be overcome in order for an atom to diffuse from its current location to a neighboring site.[15] Typical values of the proportionality constant, D_0, and the activation energy, q, are shown in Tables 2.2 and 2.3.

The diffusion welding process generally occurs during three stages. These are (1) the localized deformation of the faying surfaces under pressure at elevated temperature, (2) the diffusion of atoms across the interface, and (3) the migration of the interface. These steps do

15. Kou, S., 1996, *Transport Phenomena and Materials Processing*, New York: John Wiley and Sons.

Table 2.2
Diffusion Data for Self-Diffusion in Pure Metals

Structure	Metal	D_0 (mm^2/sec)	q (kJ/mol)
Fcc	Au	10.7	176.9
Fcc	Cu	31.0	200.3
Fcc	Ni	190.0	279.7
Fcc	Fe (γ)	49.0	284.1
Bcc	Fe (α)	200.0	239.7
Bcc	Fe (δ)	190.0	238.5

Fcc = Face-centered cubic.
Bcc = Body-centered cubic.
D_0 = Proportionally constant (the upper limit of the diffusion coefficient), mm^2/s.
q = Activation energy (kJ/mol).

Table 2.3
Diffusion Data for Interstitials in Iron

Structure	Metal	D_0 (mm^2/sec)	q (kJ/mol)
Bcc	C	2.0	84.1
Bcc	N	0.3	76.1
Bcc	H	0.1	13.4
Fcc	C	2.5	144.2

Bcc = Body-centered cubic.
Fcc = Face-centered cubic.
D_0 = Proportionally constant (the upper limit of the diffusion coefficient), mm^2/s.
q = Activation energy (kJ/mol).

not occur discretely, but overlap one another during the diffusion welding process.

During the initial stage of diffusion welding, the applied pressure causes localized deformation at the interface, resulting in an increased contact area. This process occurs more easily at higher temperatures because the yield strength of the material decreases with increasing temperature. The extent of localized deformation and the resultant surface contact is determined by factors such as surface roughness, alloy strength at the applied temperature, and applied pressure. As the contact area increases, the localized stress within each contact area decreases. Deformation occurs until the local stresses within the areas of contact are reduced below the yield strength.

At this point, the initial stage of diffusion welding is essentially complete, and the joint contains isolated voids separated by areas of intimate contact. This initial stage typically occupies only a small fraction of the total joining cycle. The first stage generally occurs more quickly as the temperature and applied pressure are increased.

During the second stage, atoms are transferred across the joint interface. Several diffusion paths are operable during this period. Mass can be transported to the interface and to trapped pores by both grain boundary and volume (bulk) diffusion mechanisms. Mass can be transported across the interface along the surfaces of trapped pores by surface diffusion. The important microstructure change that occurs at this stage is the elimination of voids at the interface. The flow of mass to the voids and through grain boundaries and volume diffusion leads to the eventual elimination of the voids.

Grain-boundary diffusion plays the major role in this step. In the grain boundaries, the atomic structure is less densely packed than that of the bulk (grain interior), and diffusion occurs much more rapidly as a result. Thus, fine-grain materials, which exhibit more grain boundary area, are more effective at eliminating voids during the second stage than coarse-grained materials are. This phenomenon is often utilized to accelerate the second stage of diffusion welding. For example, the contacting surfaces are occasionally cold-worked prior to diffusion welding so that recrystallization occurs during joining. This leads to a fine grain size and rapid mass transport to voids that are trapped in the interface.

During the last stage of diffusion welding, the original interface between the faying surfaces begins to migrate away from its original position, and the initially straight interface becomes more irregular. The voids that were originally contained at grain boundaries now move into the grain interiors. Although the diffusion processes still occurs during this final stage, the rate of mass transport is reduced to only volume diffusion to the pores. Therefore, it is not as rapid. The bonding process is essentially complete at this stage. A small number of isolated pores may still exist within the grain interiors, but they have little influence on joint integrity since they are isolated.

Because solid-state diffusion is an atomic process, the welding time is longer compared to that used for most welding processes. However, because the temperatures of the assemblies are uniform during diffusion welding and no melting takes place, assemblies with very close tolerances and low residual stress can be fabricated.

ARC CHARACTERISTICS

A welding arc can be considered a gaseous conductor that changes electrical energy into heat. The arc is the heat source for many welding processes because it produces a high-intensity heat and is easy to control by electrical means. In addition to being a source of heat, the welding arc is a source of radiation. When used in welding processes, an arc may help remove surface oxides in addition to supplying heat. The arc also influences the mode of transfer of metal from the electrode to the work.

A welding arc is a particular group of electrical discharges that are formed and sustained by the development of a gaseous conduction medium. The current carriers for the gaseous medium are produced by thermal mechanisms due to the high temperature of the arc.

Many kinds of welding arcs have been conceived, each with a unique application in the field of metal joining. In some cases, the welding arc is operated in a steady state. More frequently, it is intermittent, subjected to interruptions by electrical short-circuiting, or it is continuously unsteady, influenced by the alternating directional flow of the current with ac operation.

PLASMA

The arc current is carried by plasma, the ionized state of a gas composed of nearly equal numbers of electrons and ions of gas atoms and molecules. The electrons, which support most of the current conduction, flow out of a negative terminal (cathode) and move toward a positive terminal (anode). Mixed with the plasma are other states of matter, including molten metals, slags, vapors, neutral and excited gaseous atoms, and molecules.

The establishment of the neutral plasma state by thermal means, that is, by collision processes, requires the attainment of equilibrium temperatures according to the ionization potential of the material from which the plasma state is produced. The formation of plasma is governed by an extended concept of the ideal gas law and the law of mass action. A basic equation for the formation of plasma is the following:

$$\frac{n_e n_i}{n_o} = \frac{2Z_i(2\pi m_e kT)^{3/2}}{Z_o h^3} \exp\left\{\frac{-eV_i}{kT}\right\} \tag{2.21}$$

where

n_e, n_i, and n_o = Particle densities (number per unit volume for electrons, ions, and neutral atoms, respectively), number/m^3;
Z_i and Z_o = Partition functions for ions and neutral particles;
π = 3.1416;
m_e = Electron mass, kg;
eV_i = Ionization potential of the atom, electronvolts (eV);[16]
T = Temperature, K;
h = Planck's constant, (6.62×10^{-24} J/s); and
k = Boltzmann's constant, (1.3×10^{-23} J/K).

The particle densities of three kinds of particles can be determined by assuming that the plasma is electrically neutral and that the ions have a single positive charge. Then, the number of electrons per unit volume is equal to the number of ions per unit volume, as follows:

$$n_e = n_i \tag{2.22}$$

where n_e and n_i denote particle densities in number/m^3.

The density and distribution of argon gas particles and electrons in argon plasma between 0 K and 35 000 K are shown in Figure 2.5.

The expression of thermal equilibrium of the heated gas in an arc signifies that all kinetics and reactions of the particles in a microvolume may be represented by the same temperature. Thermal equilibrium in a welding arc is closely approached but may be considered only approximate because of the influence of dominant processes of energy transport, including radiation, heat conduction, convection, and diffusion. The heated gas of the arc attains a maximum temperature between 5000 K and 50 000 K, depending on the kind of gas and the intensity of the current carried by the plasma. The degree of ionization is between 1% and 100%. Complete ionization occurs when all the gas atoms are ionized (no neutral atoms, only ions, remain).

The attainment of a very close approximation to thermal equilibrium is more questionable in the region closest to the arc terminals, where current-conducting electrons are accelerated suddenly by a high electric

16. As joules provide exceptionally small values, eV are preferred and widely used.

LIVE GRAPH
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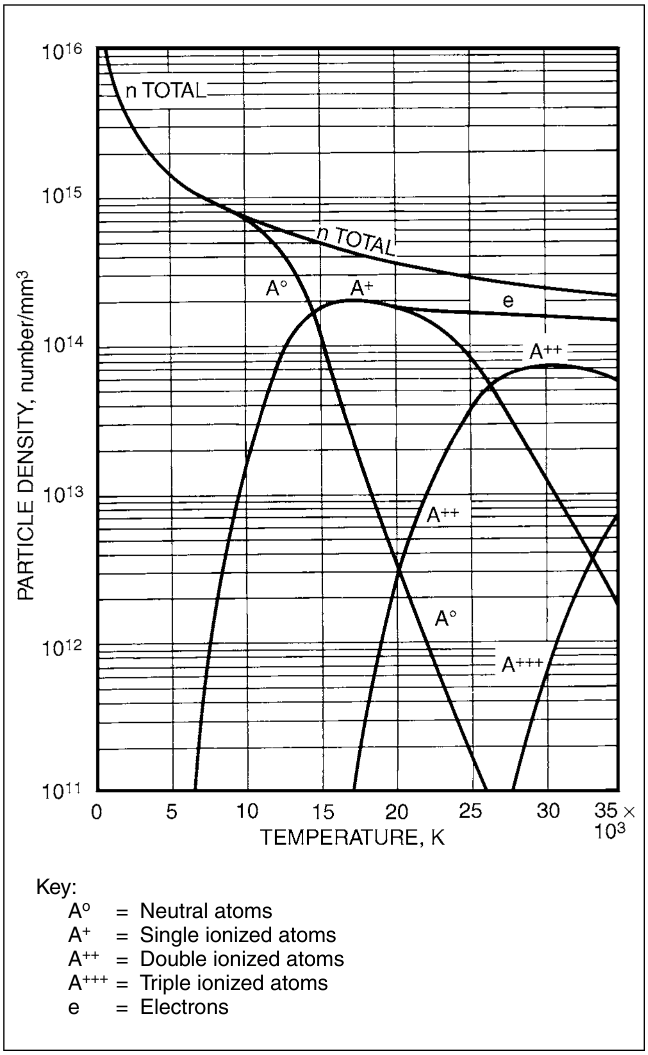

Figure 2.5—Argon-Shielded Arc Plasma Composition: 100 kPa Pressure

field and sufficient collisions may not occur. An explanation of current conduction based wholly on thermal ionization is insufficient in the arc terminal regions and must be augmented by the theory of field emission or some other concept.

TEMPERATURE

Measured values of welding arc temperatures normally fall between 5000 K and 30 000 K, depending on the nature of the plasma and the amount of current conducted. As a result of a high concentration of easily ionized materials, such as the sodium and potassium that are incorporated in the coatings of shielded metal arc welding electrodes, the maximum temperature of a shielded metal arc is considered to be around 5500 K. In pure inert gas arcs, the axial temperature may approach 30 000 K. Some special arcs of extreme power loading may attain an axial temperature of 50 000 K. In most cases, the temperature of the arc is determined by measuring the spectral radiation emitted. A thermal map of a 200 A arc in argon between a tungsten electrode and a water-cooled copper anode is shown in Figure 2.6, as obtained from spectral analysis.

The temperature of an arc is determined by the balance between the electrical power input and energy losses (due to heat conduction, diffusion, convection, and radiation) from an arc plasma of specific composition and mass flow. The energy losses from arcs vary in a complex way according to the magnitude of the temperatures and the influences of thermal conduction, convection, and radiation. In the classical Elenbaas-Heller equation of energy balance, the radial loss due to thermal conduction in the cylindrical geometry of the arc plasma is expressed as follows:

$$\sigma E^2 = -\frac{1}{r}\frac{d}{dr}\left(rK\frac{dT}{dr}\right) \tag{2.23}$$

where

σ = Electrical conductivity, 1/ohm – m or ohm/m;
E = Electrical field strength, V/m;
r = Radial position, m; and
K = Thermal conductivity coefficient, J/s K m.

To include all loss mechanisms in the energy balance requires a more involved differential equation. The thermal conductivities of several gases at 100 kPa pressure are shown in Figure 2.7. It should be noted that the data for hydrogen and nitrogen show peaks due to the effect of the thermal dissociation of the molecular form and the association of the atomic form.

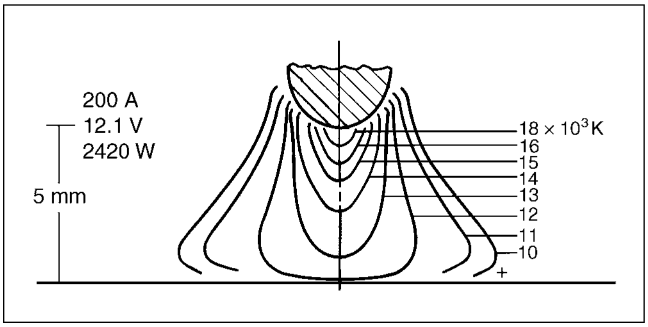

Figure 2.6—Thermal Diagram of an Argon-Shielded Tungsten Arc

LIVE GRAPH
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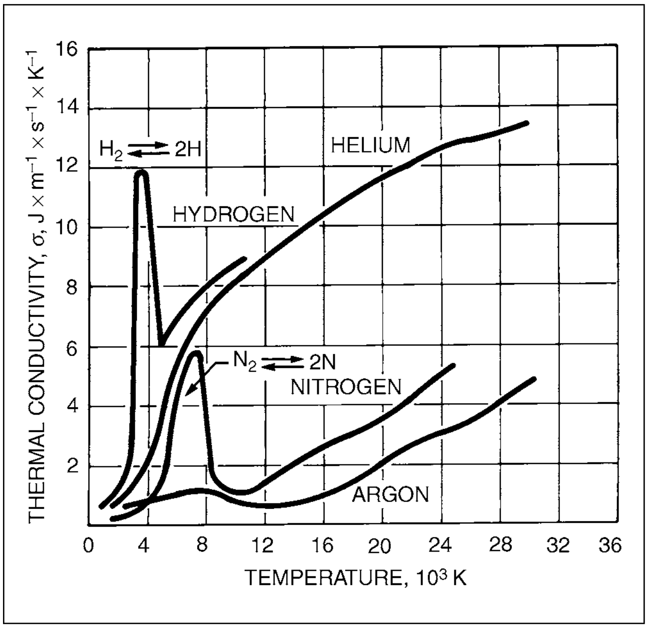

Figure 2.7—Thermal Conductivities of Several Representative Gases as a Function of Temperature

RADIATION

The amount and character of radiation emitted by an arc depend on the atomic mass and chemical structure of the gas, the temperature, and the pressure. Spectral analysis of arc radiation may show banks, lines, and continua. The analysis of radiation from organic-type covered electrodes reveals molecular bands that reveal the existence of vibrational and rotational states as well as line and continuum emissions from excited and ionized states. Inert gas arcs radiate predominantly by atomic excitation and ionization. As the energy input to the arc increases, higher states of ionization occur, producing radiation of higher energy levels.

Loss of energy due to radiation may be over 20% of the total energy input in the case of argon welding arcs, while in other welding gases the radiation loss is not more than approximately 10%. Intense radiation in the ultraviolet, visible, and infrared wavelengths is emitted by all exposed welding arcs. Ultraviolet radiation from argon-shielded arcs is particularly strong because of mass effects and because little or no self-absorption occurs within the plasma volume. The visible spectrum and a portion of the infrared spectrum emanating from an argon-shielded gas tungsten arc are shown in Figure 2.8.

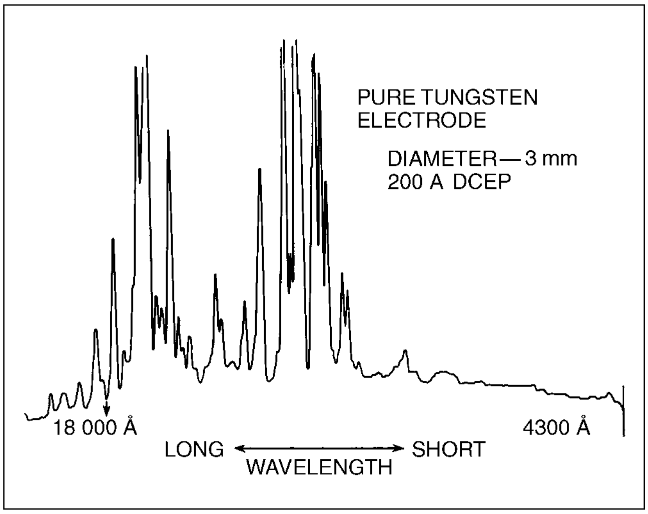

Figure 2.8—Spectrum of an Argon-Shielded Gas Tungsten Arc

ELECTRICAL FEATURES

A welding arc is an impedance to the flow of current, as are all normal conductors of electricity. The specific impedance is inversely proportional to the density of the charge carriers and their mobility, with the total impedance depending on the radial and axial distribution of the carrier density. The plasma column impedance is a function of temperature, but generally not in the regions of the arc near its terminals.

The electrical power dissipated in each of the three spaces or regions of the arc is the product of the current flow and the potential across the region. The current and potential across each region result in power dissipation in the arc according to the following equation:

$$P = I(V_c + V_p + V_a) \quad (2.24)$$

where

P = Total power dissipated in the arc, W;
I = Current, A;
V_c = Cathode voltage, V;
V_p = Plasma voltage, V; and
V_a = Anode voltage, V.

These regions are referred to as the *cathode fall space*, the *plasma column fall space*, and the *anode fall space*.

The potential distribution across the arc is shown in Figure 2.9. However, intermediate regions are taken up in expanding or contracting the cross section of the gaseous conductor to accommodate each main region. As a consequence, welding arcs assume bell or cone shapes, elliptical contours, or some other noncylindrical configuration.

Many factors may contribute to the various shapes. These include the configuration of the arc terminals, gravitational and magnetic forces, and interactions between the plasma and ambient pressures. The area over which the current flows into the arc terminals (anode and cathode spots) has a strong effect on the arc configuration and on the flow of heat energy into these terminals. The current density at the workpiece terminal is of utmost importance to the size and shape of the fusion zone as well as to the depth of fusion in a welded joint.

The total potential of an arc falls with increasing current and rises again with a further increase in current (for a fixed arc length). Typical curves are shown in Figure 2.10.

The total potential of an arc generally increases as the spacing between the arc terminals increases. Because the arc column is continually losing charge carriers by radial migration to the cool boundary of the arc, lengthening the arc exposes more of the arc column to the cool boundary, imposing a greater requirement on the charge carrier maintenance. To accommodate this loss of energy and maintain stability, the applied voltage must be increased.

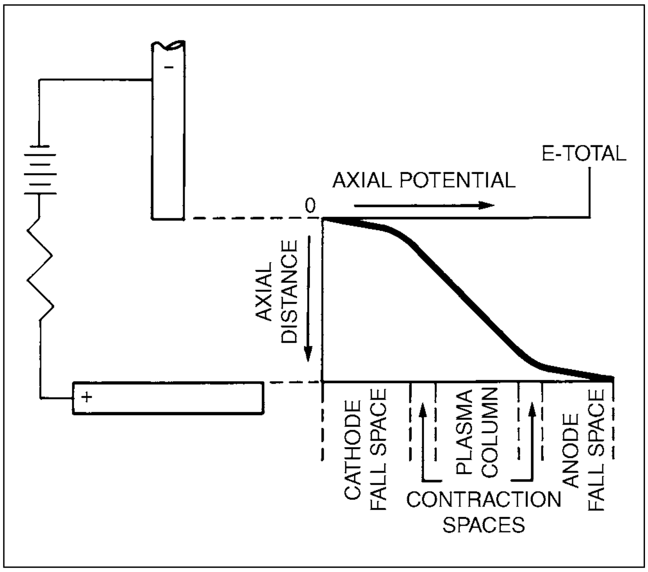

Figure 2.9—Arc Potential (V) Distribution between the Electrode and the Workpiece

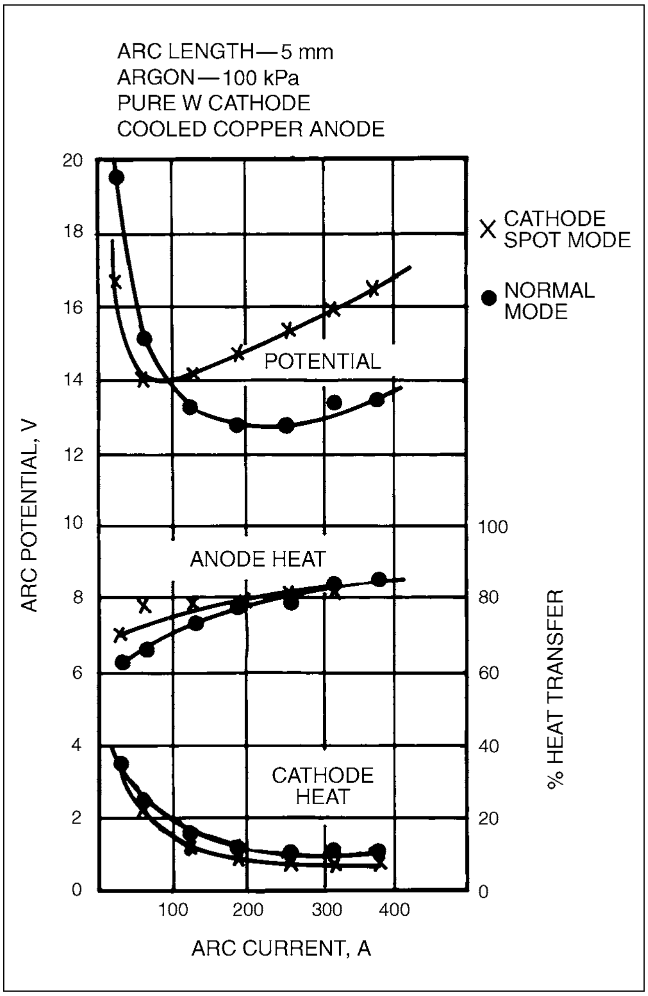

Figure 2.10—Typical Volt–Ampere and Percent Heat Transfer Characteristics of an Argon-Shielded Tungsten Arc

Much of the foregoing information concerns the plasma column, which is better understood than the mechanisms that are in effect at the arc terminals, although these mechanisms are even more important in welding arcs. The arc terminal materials must, in most cases, provide the means for achieving a continuity of conduction across the plasma column.

It is essential that the cathode material provide electrons by emission of sufficient density to carry the current. For example, in the gas tungsten arc welding process, the tungsten electrode readily emits electrons when the temperature of the electrode tip is lower than the melting point (with thoria or other additions to the tungsten). In other processes, consumable cathode materials that are melted and transferred through the arc must also provide sufficient density of electrons to carry the arc current. When consumable electrodes are used, additives to the flux, electrode, or shielding gas may be selected to ensure stable or spatter-free transfer.

INFLUENCE OF MAGNETIC FIELDS ON ARCS

Magnetism has multiple effects on welding arcs. These can be beneficial or detrimental. Magnetic fields, whether induced or permanent, interact with the arc current to produce force fields that cause arc deflection, commonly known as *arc blow* (see below). Arc blow, plasma streaming, and metal transfer are some of the welding arc characteristics that are strongly influenced by the presence of magnetic fields.

Magnetic flux results from several causes. It may be self-induced and associated with the arc current or produced by residual magnetism in the material being welded. It may also be produced by an external source. Since a welding arc always has its own associated magnetic field, any effects of external magnetic fields arise as a consequence of interaction with the self-field.

The effects of external magnetic fields on welding arcs are determined by the Lorentz force, which is proportional to the vector cross product of the external field strength and the arc current. The usual effect of external magnetic fields on arcs is to cause arc deflection. In a macroscopic sense and within the limits of stable deflection, an arc behaves as a flexible conductor that has an elastic stiffness that resists the overall Lorentz force. The arc deflects in a smooth curve from a fixed point at the electrode tip to the base metal. The magnitude of the arc deflection is proportional to the applied field strength. The direction of the Lorentz force—and consequently the arc deflection—is determined by Fleming's left-hand rule for arc deflection, illustrated in Figure 2.11.

Arc deflection may be understood intuitively if flux lines are considered as encircling a conductor, adding vectorially to the applied field lines on one side and canceling the applied field lines on the other side. The arc will be deflected toward the weak flux side. Arc deflection in the direction of travel (forward deflection) results in a more uniform weld that may be wider with less penetration. Forward arc deflection results in improved bead appearance and reduced undercut at higher welding speeds.

Arc deflection can also be affected by the proximity of multiple arcs. A two- or three-wire submerged arc welding operation utilizes the magnetic fields of neighboring arcs to obtain higher travel speeds without undercut. The heavy undercutting and extensive reinforcement associated with backward arc deflections have little use in practical welding.

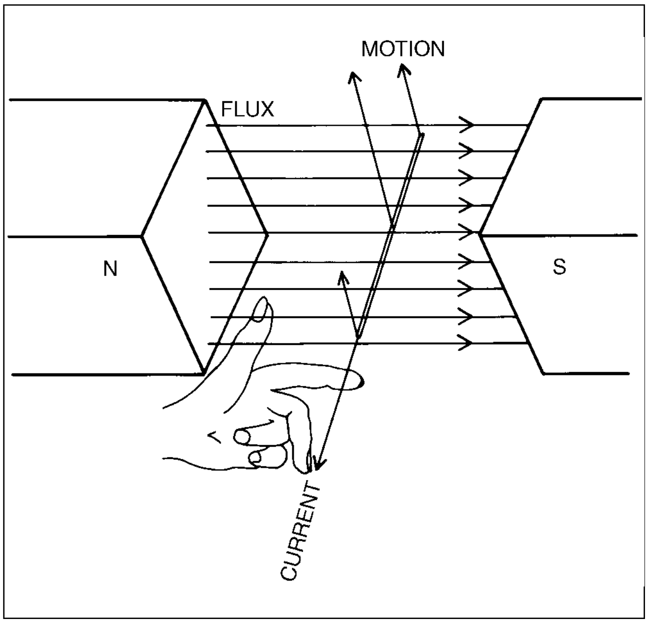

Figure 2.11—Fleming's Left-Hand Rule for Arc Deflection

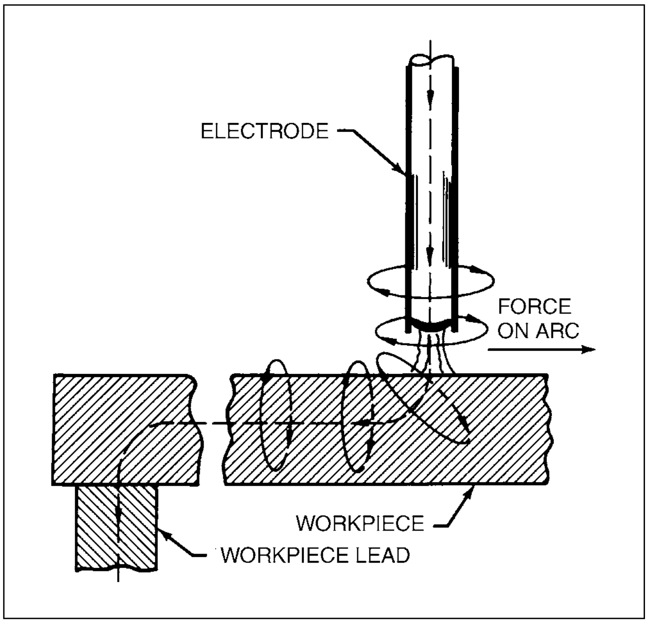

Figure 2.12—Force on the Arc by the Induced Magnetic Field Resulting from the Workpiece Lead Location

Alternating magnetic fields cause the arc to oscillate back and forth across the weld axis with a frequency equal to that of the applied field. This phenomenon is used to advantage in the gas tungsten arc welding hot-wire process, in which the arc is deflected in a controlled manner by the magnetic field around the hot filler wire.

Arc Blow

Under certain conditions, the arc has a tendency to be forcibly directed away from the point of welding, thereby making it difficult to produce a satisfactory weld. This phenomenon, termed *arc blow*, is the result of magnetic disturbances surrounding the welding arc. In general, arc blow is the result of the following two basic conditions:

1. The change in direction of the current flow as it enters the work and is conducted toward the work lead, and
2. The asymmetric arrangement of magnetic material around the arc, a condition that normally exists when welding is performed near the ends of ferromagnetic workpieces.

Although arc blow cannot always be eliminated, it can be controlled or reduced to an acceptable level by taking these two conditions into consideration. The first condition is illustrated in Figure 2.12. The dotted line traces the path of the current through the electrode, the arc, and the workpiece. Magnetic lines of force surround the current path. The lines of force are represented schematically as circles concentric with the current path. They are concentrated on the inside of the bend in the current path and are sparse on the outside curve. Consequently, the magnetic field is much stronger on the side of the arc toward the workpiece connection than on the other side. Moreover, according to Fleming's left-hand rule, this force is always in a direction away from the work connection. Thus, welding away from the workpiece connection produces more favorable forward arc blow.

The second condition is illustrated in Figure 2.13. It is much easier for magnetic flux to pass through a magnetic material than through air. Therefore, it concentrates in the steel base metal and takes the shortest air distance, which is between the beveled edges of the seam. When the arc is near one end of the seam, the magnetic flux lines become more concentrated between the arc and the ends of the plates. The resulting effect on the arc is shown in Figure 2.14.

As a rule, the magnetic material around the arc exerts force on the arc toward the best magnetic path. When welding, the total force tending to cause the arc

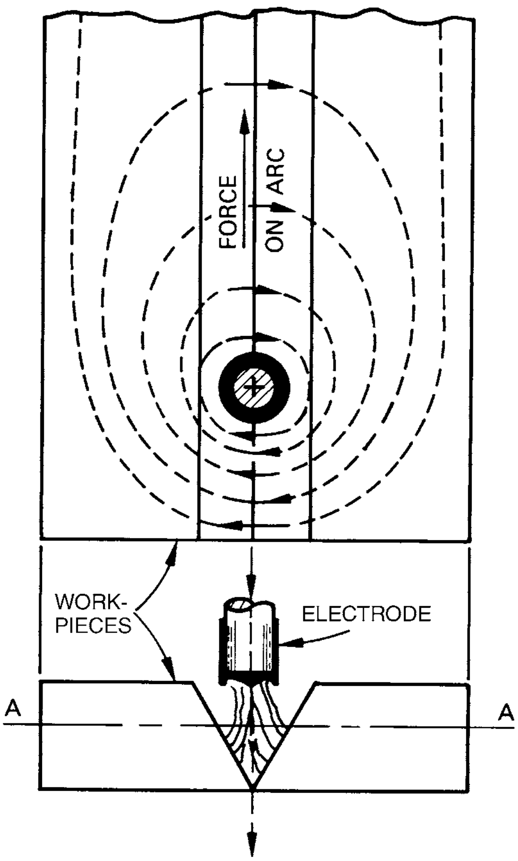

Figure 2.13—Distortion of Induced Magnetic Field at the Edge of a Steel Plate

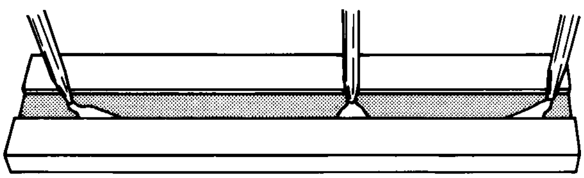

Figure 2.14—Arc Blow at the Ends of a Ferromagnetic Workpiece

to blow is nearly always a combination of the two forces illustrated in Figures 2.12 and 2.13. When welding with alternating current (ac), the magnetic effect on the arc is lessened by eddy currents induced in the work, as shown in Figure 2.15. Low voltage results in a short, stiffer arc that resists arc blow better than a long higher-voltage arc.

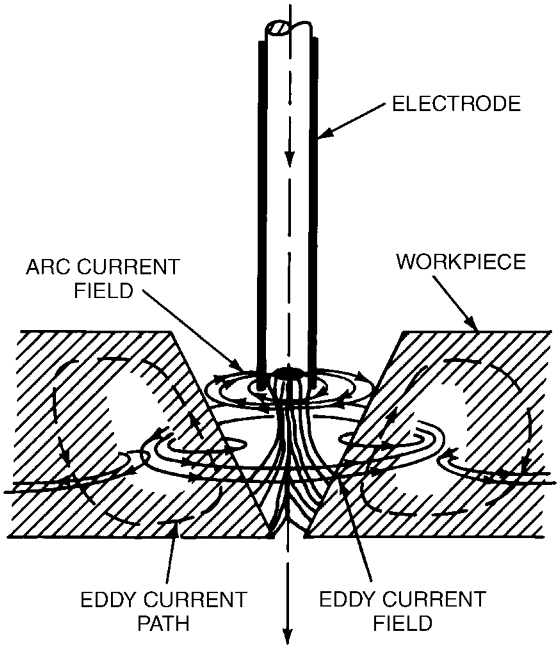

Figure 2.15—Effect of Eddy Currents in Neutralizing Magnetic Field Induced by Alternating Current

METAL TRANSFER

Arc welding processes that use consumable electrodes are used extensively because filler metal is deposited more efficiently and at higher rates than is possible with other welding processes. To be most effective, the filler metal should be transferred to the workpiece from the electrode with minimum loss due to spatter. Uncontrolled short circuits between the electrode and the workpiece should be avoided; otherwise, the welder or welding operator may have difficulty controlling the process. In the gas metal arc welding process, arc instability caused by erratic transfer can generate pressure fluctuations that draw air into the vicinity of the arc.

GLOBULAR AND SPRAY TRANSFER

The different modes of metal transfer have been studied with high-speed cinematography and video as well as by means of the analysis of short-circuit oscillograms. Transfer through the arc stream of covered electrodes can be characterized as a globular (massive drops) or a showery spray (a large number of small drops). The globular and spray modes are rarely found alone. Generally, the material is transferred in some combination of both types.

Transfer with the gas metal arc welding process varies greatly when used with argon shielding. When the current is above the transition level, the transfer mechanism can be best described as an axial spray, and short circuits are nonexistent. However, when helium or an active gas such as carbon dioxide is used for shielding, the transfer is globular, and some short-circuiting is unavoidable. The gas metal arc welding short-circuiting arc process has been adapted to use only short circuits for the transfer of metal to the pool.

The physics of metal transfer in arc welding is not well understood. Research is complicated by the fact that the arcs are very small and their temperatures and rates of metal transfer are extremely high. Because of the difficulty involved in identifying and establishing the mechanisms that regulate the process, a great number of mechanisms have been suggested. The following forces have been considered:

1. Pressure generated by the evolution of gas at the electrode tip,
2. The electrostatic attraction between the electrodes,
3. Gravity,
4. The "pinch effect" caused by electromagnetic forces on the tip of the electrode,
5. Explosive evaporation of the necked filament between the drop and electrode due to the very high density of the conducting current,
6. Electromagnetic action produced by a divergence of current in the plasma around the drop, and
7. Friction effects of the plasma jet.

In all probability, a combination of these forces functions to detach the liquid drop from the end of the electrode.

EFFECT OF POLARITY ON METAL TRANSFER IN ARGON

In arc welding, the direct current electrode positive (DCEP) mode is achieved by connecting the direct current leads in such a way that the electrode is the positive pole and the workpiece is the negative pole of the welding arc. In the direct current electrode negative (DCEN) mode, the direct current arc welding leads are connected to make the electrode the negative pole and the workpiece the positive pole.

Electrode Positive

At low welding currents in argon, liquid metal from the electrode is transferred in the form of drops or globules having a diameter greater than that of the electrode. This is referred to as *globular transfer.* With electrode positive, the drop size is roughly inversely proportional to the current, and the drops are released at the rate of a few per second. With a sufficiently long arc to minimize short circuits, drop transfer is reasonably stable and associated with a relative absence of spatter.

Above a critical current level, however, the characteristics of this transfer change to the axial spray mode. In axial spray transfer, the tip of the electrode becomes tapered, and minute drops are transferred at the rate of hundreds per second. The current at which this occurs is known as the *transition current*. Often, as in the case of steel, this change is very abrupt. Axial spray transfer is unique and valued not only for its stability but also because of the absence of spatter. Furthermore, the drops are transferred in line with the electrode rather than along the shortest path between the electrode and workpiece. The metal can therefore be directed where needed when making vertical or overhead welds.

A key to spray transfer is the pinch effect that squeezes drops off of the electrode. The pinch effect occurs as a result of the electromagnetic effects of the current, as illustrated in Figure 2.16.

The transition current is dependent on a number of variables, including electrode composition, diameter, electrode extension, and the shielding gas composition.

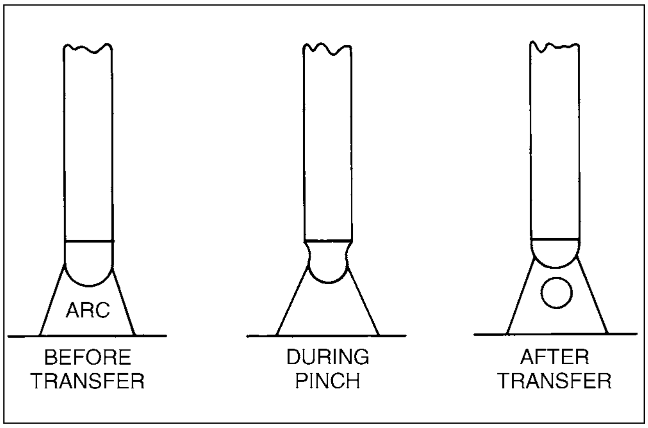

Figure 2.16—Individual Drop Formation Sequence in Spray Transfer

A great difference in transition current is found with various metal systems. Transition currents for various sizes of steel and aluminum electrodes are shown in Table 2.4.

The transition current is approximately proportional to the diameter of the electrode, as shown in Figure 2.17. The transition current is not dependent on the current density, but it is mildly dependent on the electrode extension. An increase in the extension allows a slight decrease in the current at which spray transfer develops. In practical welding operations, electrode extension is usually 13 mm to 25 mm.

When using the gas metal arc welding process to weld steels, the spray arc mode is most often used with argon-based shielding gas. The transition current defines the lower limit of useful current for spray transfer. Small amounts of oxygen are added to the shielding gas to lower the transition current slightly; additions of carbon dioxide raise the transition current.

At high welding current densities, a rotary arc mode takes place. With appropriate mixtures of shielding gases, wire feeding controls, and welding guns that perform well at high wire-feed speeds, the rotating mode of gas metal arc welding can be used to deposit as much as 7 kg/h or more of steel weld metal. The useful upper current limit is the value at which the rotational arc becomes unstable with loss of puddle control and highly increased amounts of spatter.

The welding current at which axial spray disappears and rotational spray begins is proportional to the electrode diameter and varies inversely with electrode extension. The influence of electrode diameter and electrode extension on drop-to-spray transition current for mild steel is illustrated in Figure 2.18.

Spray transfer can also be achieved at average current levels below the transition current using pulsed welding current. One or more drops of filler metal are transferred at the frequency of the current pulses. This technique increases the useful operating range of a given electrode size.

Solid-state power sources that simplify the setup for pulsed power welding have increased the applications of pulsed spray welding. The relatively low average current levels permit the out-of-position welding of steel at relatively high deposition rates.

Table 2.4
Approximate Arc Currents for Transition from Drop to Spray Metal Transfer

Electrode Diameter, mm	Transition Current, A*	
	Steel Ar + 2% O_2	Aluminum Argon
0.75	155	90
0.90	170	95
1.15	220	120
1.60	275	170

*The transition current varies with electrode extension, alloy content, and shielding gas composition.

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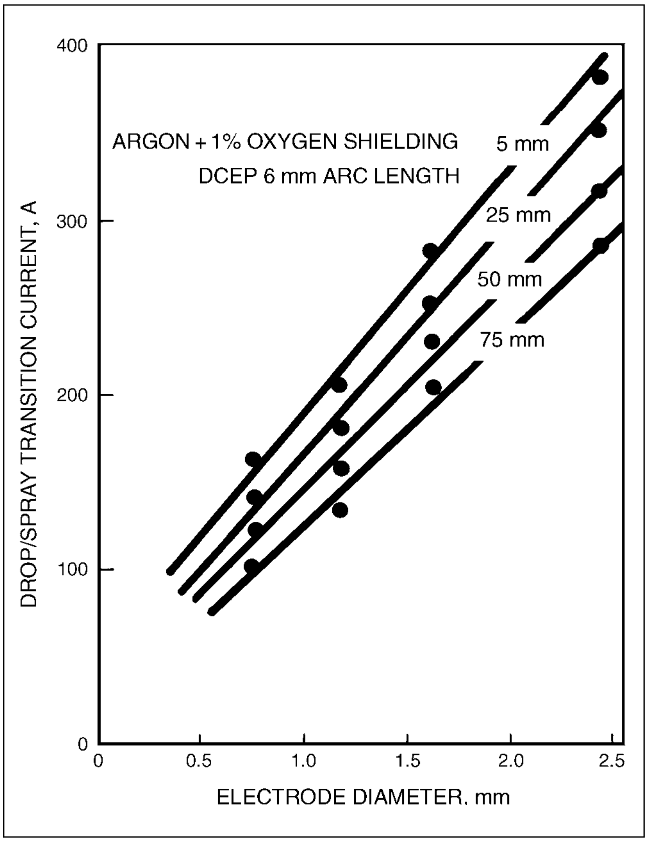

Figure 2.17—Influence of Electrode Diameter and Extension on Drop-to-Spray Transition Current for Mild Steel

Electrode Negative

The gas metal arc welding process is normally used with direct current electrode positive (DCEP) power. When the electrode is negative, the arc becomes unstable, and spatter is excessive. The drop size is large, and arc forces propel the drops away from the workpiece. This action appears to result from a low rate of electron emission from the negative electrode. If the thermionic properties of the electrode are enhanced by light coatings of alkali metal compounds such as rubidium or cesium, metal transfer is significantly improved. Although the use of emissive electrode coverings allows spray transfer in gas metal arc welding with DCEN, commercial filler metals are not available with such coatings.

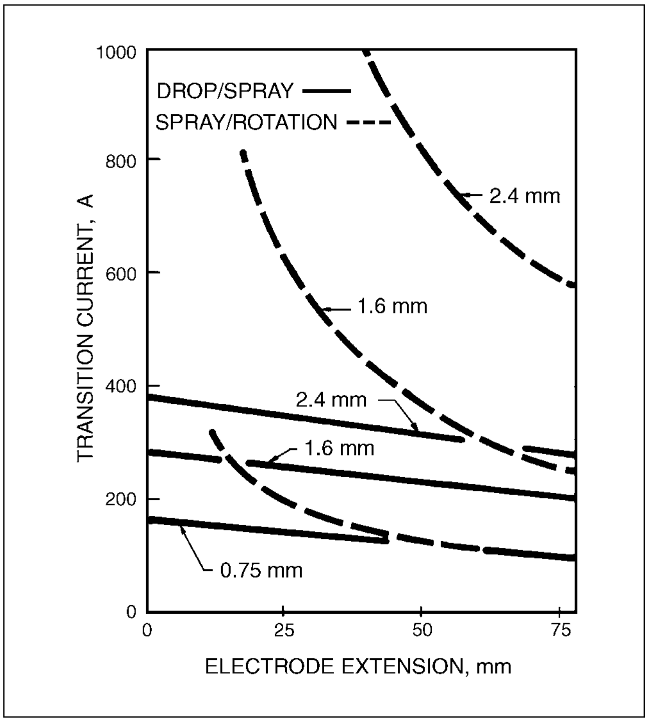

Figure 2.18—Effect of Electrode Extension and Diameter on Transition Current of Steel Filler Metals

EFFECT OF OTHER GASES ON METAL TRANSFER

Although helium is inert, it is unlike argon for shielding a welding arc because it usually fails to produce an axial spray arc. Instead, the transfer is globular at all current levels and with both polarities. Helium-shielded arcs are useful, nevertheless, because they will provide deep penetration. Spray transfer is produced in helium by mixing relatively small quantities of argon with the helium. When dilute mixtures are used, the deep penetration is not adversely changed. Although 20% argon in helium is sufficient to achieve these results, the usual commercial mixtures contain 25% argon. Argon-helium mixtures are used for welding nonferrous materials such as aluminum and copper. Generally, the thicker the material to be joined, the higher the percentage of helium is used in the shielding gas.

Active gases such as carbon dioxide and nitrogen have much the same effect as helium. Spray transfer cannot be achieved without treating the wire surface. In addition, greater instabilities in the arc and chemical reactions between the gas and superheated metal drops cause considerable spatter. The difficulty with spatter can be minimized by welding with the buried-arc technique. This technique is common when carbon dioxide is used to shield copper and when nitrogen is mixed with argon to shield aluminum alloys.

To offset the coarse globular transfer and excessive spatter associated with carbon dioxide shielding, argon may be added to stabilize the arc and improve metal transfer characteristics. Short-circuiting transfer is optimized by using mixtures of 20% to 25% carbon dioxide in argon. Higher percentages of carbon dioxide are used for joining thick steel plate.

Small amounts of oxygen (2% to 5%) or carbon dioxide (5% to 10%) are added to argon to stabilize the arc, alter the spray transition current, and improve wetting and bead shape. These mixtures are commonly used for welding steel.

SHORT-CIRCUITING TRANSFER

The short-circuiting transfer of the metal from the electrode tip to the molten weld pool has several advantages. Metal deposited in this way is less fluid and less penetrating than that formed with the spray transfer. It is easily handled by the welder in all positions, and it is particularly useful for joining thin materials. The spatter normally associated with short circuits is minimized with the use of electrical inductance or feedback to control the rate of current rise when the wire and pool are in contact. As a result, the peak value of current at short-circuit is relatively low. The average current is kept low by using small-diameter electrodes.

With the proper adjustment of equipment, the rate of short-circuiting is high (on the order of hundreds of shorts per second). As little time is available to melt the electrode, the drops formed on the tip are very small. The drops are transferred to the weld by surface tension when the electrode tip and weld pool come in contact.

The cycle of changes in current and voltage that characterize short-circuiting transfer are shown in Figure 2.19. The cycle begins when the wire contacts the weld pool. The current surges to a level high enough to cause the interface between the solid wire and liquid pool to "neck down" and finally vaporize, transferring a metal drop to the molten pool. An arc is formed with relatively high current and voltage. The high current and voltage cause the electrode tip to melt. However, immediately after the arc is established, the current decreases from its short-circuit peak. The electrode advances toward the weld pool, eventually causing another short circuit, and the cycle repeats.

PULSED CURRENT CONSUMABLE ELECTRODE TRANSFER

Pulsed current transfer is achieved by pulsing the welding current back and forth between the globular

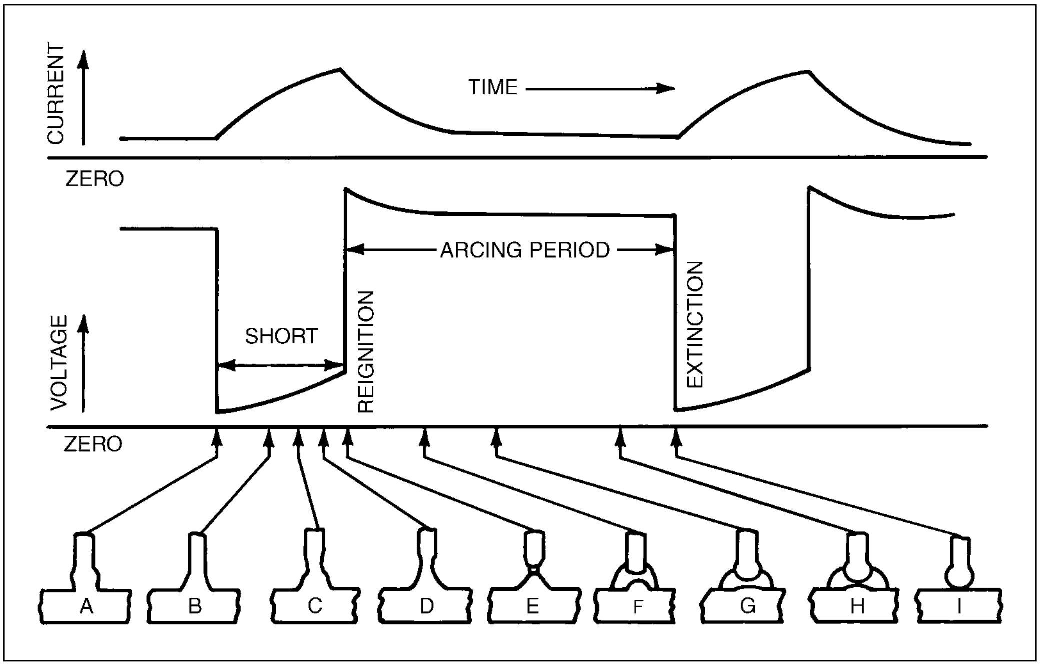

Figure 2.19—Schematic Representation of Short-Circuiting Metal Transfer

and spray-transfer current ranges. To suppress globular transfer, the time period between consecutive pulses must be shorter than that required for transfer by the globular mode.

Conversely, the pulse duration must be long enough to ensure that transfer by the spray mode occurs with an appropriate current in the spray transfer range. The pulsed current mode of transfer differs from normal spray transfer in that metal transfer is interrupted between the current pulses.

Pulse shape and frequency may be varied over a wide range. Using microcomputer technology and solid-state power sources, the pulse power can be coordinated with the electrode feed rate in such a way that a single drop of molten metal is transferred with each pulse. Both synergic and adaptive systems have been developed to employ pulsed gas metal arc welding with relative ease on both ferrous and nonferrous materials. A one-knob welding process control system can be used where the proper relationship between the pulse rate and the feed rate is maintained.

Many methods can be used to generate a modulated direct current (dc) for pulsed current transfer. The current is comprised of a background and a pulse current. Pulsating currents are illustrated in Figure 2.20, which also shows the metal transfer sequence. With pulsed power, currents and deposition rates can be decreased to permit welding of sheet as thin as 1.0 mm or even thinner with torch movement.

SUBMERGED ARC TRANSFER

Direct observation of metal transfer in the submerged arc welding process is impossible because the arc is completely obscured by a flux blanket. The submerged arc plasma is essentially a slightly ionized vapor column with a core temperature of about 6000 K. This central core is surrounded by thin concentric zones at lower temperatures with a steep radial temperature gradient. This gradient terminates at an indefinite vapor-liquid phase boundary at the boiling temperature of the flux components.

Oscillographic studies indicate that the current may be carried simultaneously through the ionized vapor and liquid phases. In commercial fluxes, the major portion of the current is carried through the vapor phase. The transfer of the metal from the electrode to the molten weld pool is undoubtedly in the form of globules and fine droplets, depending on the current.

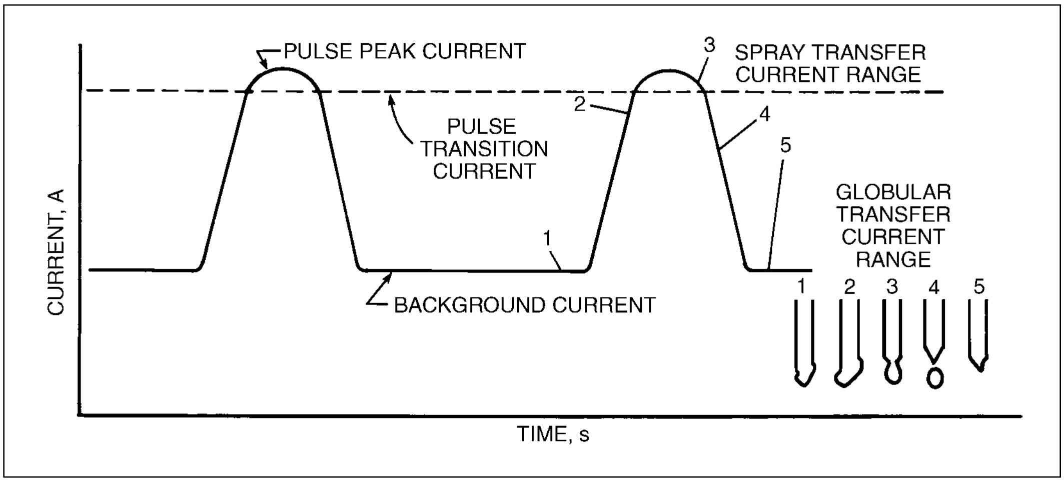

Figure 2.20—Output Current Wave Form of a Pulsed-Current Power Source and Metal Transfer Sequence

SHIELDED METAL ARC TRANSFER

The mechanism of metal transfer with covered electrodes is difficult to observe and establish because the arc is partially obscured by fume and particles of slag. In many cases, a deep cavity formed by the electrode covering hides the tip of the electrode from view. During transfer, the metal generally consists of either globules that short-circuit the arc or a fine, showery spray of metal and slag particles that do not create a short circuit. The showery spray transfer is desirable. In some cases, however, spray transfer cannot be used because it is associated with great quantities of spatter. Covered electrodes are fed manually and used with considerable manipulation. Therefore, arc stability and metal transfer mode depend on the skill of the welder.

Most electrode coatings contain cellulose or metal carbonates that dissociate in the arc, forming a gas shield to protect the weld metal from atmospheric contamination. This shield consists primarily of the active gases, carbon dioxide, carbon monoxide, hydrogen, and oxygen. The arc plasma developed by these gases is not highly conductive. The current distribution is such that the liquid metal is forced away from the arc and the weld pool in massive drops and spatter. Because these reactions are more intense when the electrode is negative, reverse polarity is normally used with the covered electrodes that do not contain cathode stabilizers (E6010, E7015).

Electrode coverings are designed to provide thermionic characteristics to the electrode. Rutile, lime, and iron oxide are generally used in combination for this purpose. Such electrodes produce a more stable arc, diminish spatter, and form smaller drops with direct current electrode negative. Included in this type are the E6012, E6020, and the varieties with high percentages of iron powder.

The stability of arcs with alternating current is dependent on re-ignition of the arc during the interval when polarity is changed and the current has been reduced to zero. Stability is frequently achieved by substituting potassium silicate for sodium silicate. The potassium forms a lower ionization path between the electrode and work and increases the cathode emissive properties to permit an easy re-ignition of the arc. Electrodes containing large quantities of rutile or lime are also thermionic, and they do not require a potassium silicate binder for ac welding.

FLUX CORED ARC TRANSFER

In flux cored arc welding (FCAW), metal transfer with flux cored wire is a combination of the basic gas metal arc welding transfer types and the shielded metal arc (covered electrode) transfer. Metal can be transferred in the globular, short-circuiting, spray, and pulse modes. The type of transfer depends on the formulation of the flux as well as the arc voltage and current.

MELTING RATES

The term *melting rate* refers to the weight or length of electrode (wire, rod, or powder) melted in a unit of time. The melting rate of an arc welding electrode is important because it is the major factor determining the deposition rate of the weld filler material.

GENERAL CONTROLLING VARIABLES

As discussed previously, heat in an arc is generated by electrical reactions at the anode and cathode regions and within the plasma. Portions of this energy melt the electrode, unless it has a very high melting point and is adequately cooled. The greatest portion of the arc energy for melting is obtained from cathode or anode reactions, depending on the polarity. Substantially more heat can be released from the cathode and deposited in the electrode when operating DCEN (excluding tungsten electrodes). Furthermore, when the electrode is the cathode (negative) terminal, good control of the energy release is possible. Little can be done to modify the release of energy at the anode (positive) terminal because it is mostly related to the current magnitude and weakly related to composition and other factors.

Most commercial metals and their alloys form what is called a *cold cathode*. The area of the cold cathode is rather small, but great quantities of energy are generated to release the electrons needed to support an arc. However, metals that have very high melting points easily supply electrons to sustain the arc at high temperature. These metals are termed *thermionic*. Included in this thermionic category are molybdenum and tungsten.

Cold-cathode, low-melting-point metals can be made to supply electrons more easily by coating them with compounds that reduce the surface work function. The metals then become thermionic at lower temperatures. In some cases, the mechanism of electron release depends on surface oxide emission. In others, it is due to the formation of an atomic film of an alkali metal on the surface. The degree of change is regulated by the selection of the type and quantity of oxides or metals. In general, the change from cold-cathode to thermionic emission is accompanied by a lowering of the heating energy, and therefore a reduction in the melting rate. Any improvement in the mode of metal transfer with DCEN or in arc stability with ac is associated with a reduction in melting rate.

The arc plasma supplies relatively little heat to the electrode in comparison to the electrode voltage drop region. Therefore, those variables affecting the plasma, such as the shielding gas, flux, or the arc length, do not directly affect melting rate. If a change in melting rate is demonstrated, it is more likely caused by another factor, such as a change in current or cathode heating.

In addition to the energy supplied by the welding arc, electrical resistance heating of the electrode by welding current affects the melting rate of the electrode. This heating is caused by the resistance of the electrode to the flow of the current. This effect is particularly significant in welding processes that use small-diameter electrodes. Electrical resistance is greater with small-diameter electrodes, long electrode extensions, and low-conductivity metals and alloys. The relationship of all these variables to the electrode melting rate can be expressed as follows:

$$MR = aI + bLI^2 \tag{2.25}$$

where

MR = Electrode melting rate, kg/hr;
a = Constant of proportionality for anode or cathode heating, whose magnitude is dependent on polarity, composition, and, with DCEN, the emissivity of the cathode, kg/h × A;
b = Constant of proportionality for electrical resistance heating and includes the electrode resistivity, kg/h × A^2 mm;
L = Electrode extension ("stickout"), mm; and
I = Welding current, A.

GAS METAL ARC WELDING

The melting rate associated with the gas metal arc welding process is controlled by (1) the electrode diameter and extension and (2) the cathode or anode heating. Heating is dependent on the electrode polarity as well as the magnitude of the welding current. The shielding gas, the arc length, and the arc voltage have no significant effect on the melting rate.

Equation (2.25) can be used to calculate melting rates with electrode positive. Problems develop with DCEN because the cathode heating value is very sensitive to the presence of oxides and alkali and alkaline-earth compounds. Gas metal arc welding is not commonly operated with DCEN, however.

The first term of Equation (2.25) is more significant at low currents and with short extensions of the electrode. The influence of the second term becomes progressively greater with smaller electrodes, increased electrode extension, and higher welding current. The relative magnitude of the heating coefficients with wire diameters of 1.6 mm is shown in Table 2.5.

The values of *a* and *b* in Equation (2.25) are dependent on the composition of the electrode. For example, the first term is of greater significance with aluminum electrodes because the electrical resistance is low. It is also more important when the electrode is negative since the use of any additive that affects the electron emissivity of the cathode also reduces the magnitude of term *a* in Equation (2.25).

An example of the effect of an additive on the melting rate is shown in Figure 2.21. The electrode can be made sufficiently thermionic to reduce the heating effect represented by term *a* for DCEN power below that of

Table 2.5
Relative Magnitude of Heating Coefficients in the Melting Rate of 1.6 mm Diameter Wire Electrode

	a	*b*
	kg/h × A	kg/h × A^2 mm
Aluminum (DCEP)	5.4×10^{-3}	4.4×10^{-6}
Mild steel (DCEP)	8.6×10^{-3}	2.5×10^{-5}
Mild steel (DCEN)	1.8×10^{-2}	2.5×10^{-5}

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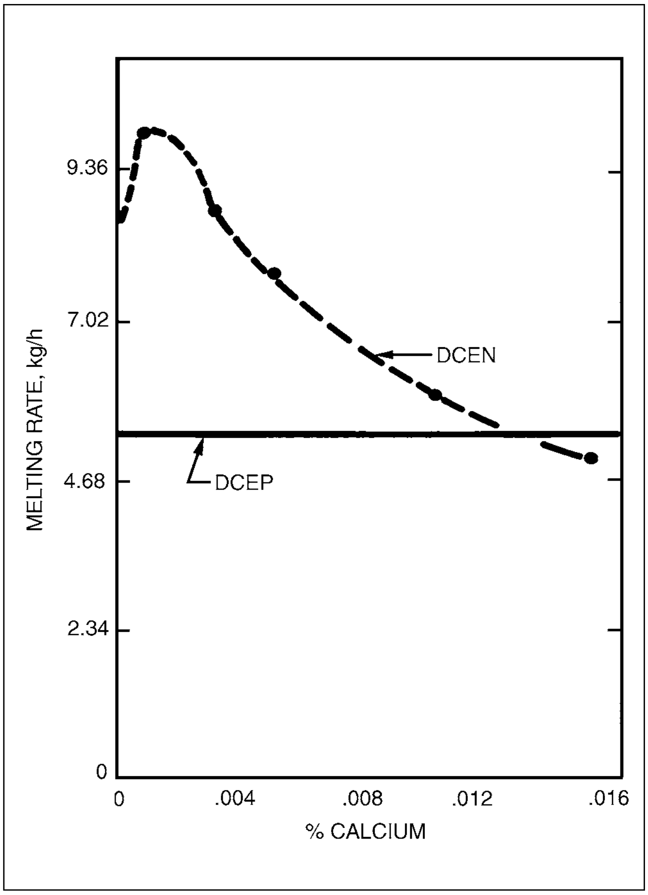

Figure 2.21—Effect of the Percentage of Calcium in the Electrode Coating Compound on the Melting Rate of 1.6 mm Diameter Mild Steel Electrodes

DCEP power. Direct current electrode negative arcs have great appeal because their melting rates can be so high. Unfortunately, when melting rates are high, the transfer of metal can be globular and spattery. Improvements in transfer gained by making the cathode more thermionic are accompanied by a reduction in melting rate. When ac is used, the magnitude of term *a* in Equation (2.25) is an average of the values obtained at direct current with electrode negative and electrode positive.

The usable range of the melting rate is limited by a number of undesirable effects. When argon shielding is used, the current at which drop transfer begins defines the lower limit of melting rates. This varies with the electrode diameter since lower currents can be used with smaller wire diameters. The melting rate is not always reduced significantly by this expedient because the resistance of the electrode increases as the diameter decreases, and the second term of Equation (2.25) contributes significantly to the melting rate. The upper limit of the melting rate is defined by the formation of unstable arc rotation. Since the onset of unstable arc rotation increases with the electrode diameter, high-current arcs are generally sustained with the large-diameter electrodes.

The extent of these ranges is shown in Figure 2.22 for steel. This factor is particularly important with steel

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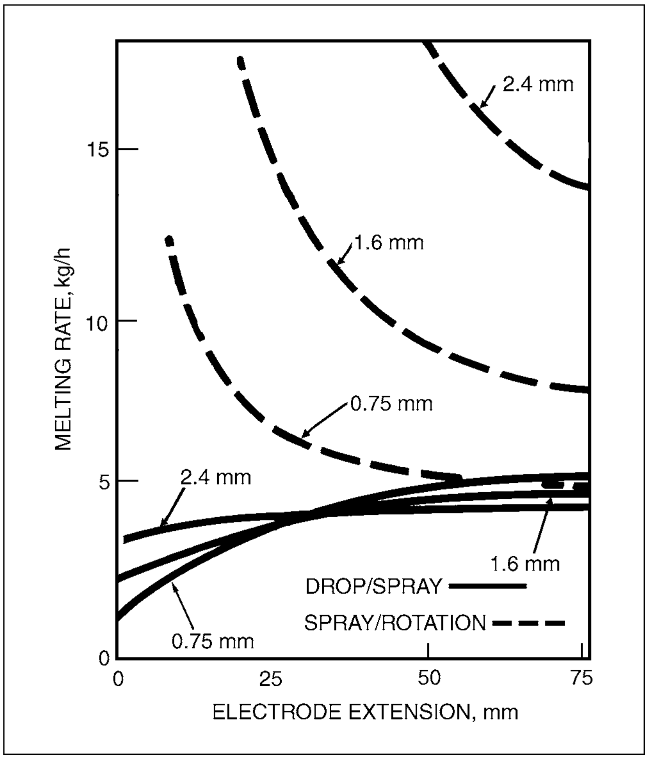

Figure 2.22—Useful Ranges of Melting Rates of Mild Steel Electrodes

but is of little significance with aluminum. A rough weld surface condition prevents the use of very high currents in welding aluminum.

The current limits of arcs in active gas shields are not determined on the basis of metal transfer since the transfer is always globular. The lower level of current is established by random short-circuiting, the absence of wetting, and other conditions that result in poor weld quality. The upper limit of current is determined in substantially the same way—the presence of spatter, poor bead appearance, and porosity.

SUBMERGED ARC WELDING

The preceding comments for gas metal arc welding generally apply to the submerged arc welding process. The melting rate of the electrode increases as the current increases. The exact melting rate is influenced by changes in the anode or cathode voltages produced by changes in flux composition or changes in voltage level, travel speed, or in electrode preheat. The melting rate for mild steel electrodes in the submerged arc welding process is often reported as 13.9 kg/h-kA and ranges from approximately 11 kg/h-kA to over 16 kg/h-kA, depending on electrode extension, polarity, and composition.

SHIELDED METAL ARC WELDING

Compared to gas metal arc welding and submerged arc welding, the shielded metal arc welding process is less efficient in converting electrical energy to useful weld heat. This inefficiency is due in part to the need for melting a flux along with the core wire. Most important, however, is the absence of extensive electrical resistance heating. The diameters of the electrodes are so large that anode or cathode heating is the primary source of energy. Control of the melting rate, therefore, is achieved largely by adjusting the current. With shielded metal arc welding, the range of current that can be used with covered electrodes is more limited than the range that can be used with the gas metal arc welding or submerged arc welding processes. As the current requirements increase, the electrode diameter must increase.

The lower limit of current is defined by incomplete fusion, high viscosity of the flux, or an unstable globular transfer. The upper current is limited by the excessive temperature of the core wire of the electrode due to electrical resistance heating. The heated core wire damages the electrode covering. The heating of some materials in the covering (e.g., cellulose material and carbonates) causes these constituents to break down before reaching the arc where the products of dissociation are needed for shielding.

Overheating may also cause the electrode covering to spall. Some coverings are more susceptible to damage by overheating than others. For example, the cellulose-containing E6010 electrode of 6 mm diameter is useful in the range between 200 A and 300 A, whereas for the same diameter, the rutile-base E6012 that does not rely on gas formers has a useful range between 200 A and 400 A.

Iron powder electrodes were introduced to provide higher melting rates and better material transfer than were possible with the conventional mineral coverings. Because iron is contained in the covering, the melting rate for a given current is higher. However, the optimum current needed to obtain an acceptable weld appearance is also higher with iron powder electrodes. The increase in current is proportional to the amount of iron contained in the covering. Therefore, higher melting rates for a given electrode diameter are achieved by a combination of increased efficiency and higher current. The results of these effects are shown in Figure 2.23.

PHYSICAL PROPERTIES OF METALS AND SHIELDING GASES

The physical properties of the metals or alloys being welded have an influence on the efficiency and applicability of the various welding processes. The nature and properties of the shielding gases and of the contaminants from the atmosphere may have a pronounced effect on the resulting weld. The shielding gases may be generated either by the decomposition of fluxing materials or by their direct introduction into the arc stream and the area surrounding the arc plasma.

Both thermal conductivity and thermal expansion have a direct effect on distortion of the weldment. Base metal electrical resistivity and thermal conductivity have a pronounced effect on the application of both resistance and arc welding to the various metals. In resistance welding (RW), base metal resistivity, thermal conductivity, and specific heat influence the power requirements.

In arc welding, arc initiation and arc stability are greatly influenced by the ionization potentials of the metal and flux vapors as well as by the various electronic transitions that occur in the shielding gases under the extreme temperature conditions that exist in the arc.

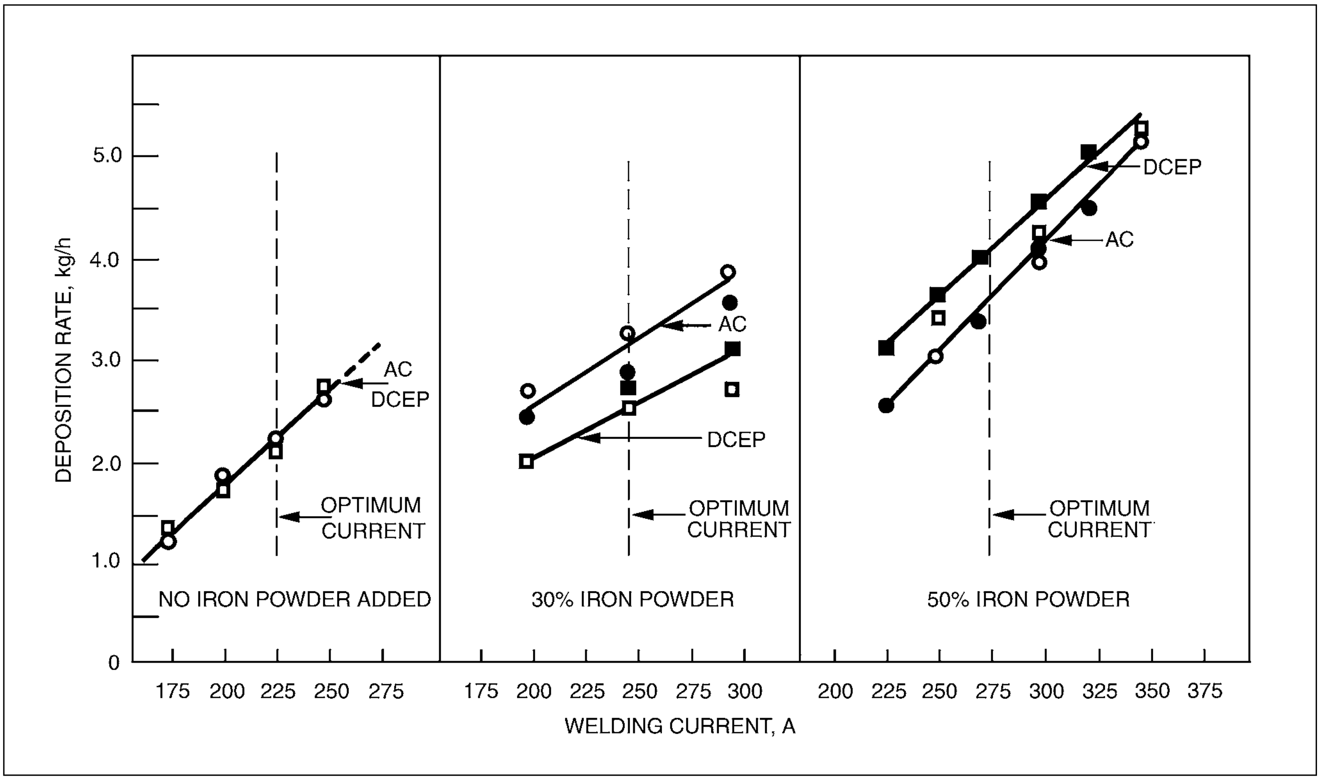

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Figure 2.23—Effect of Welding Current on Deposition Rates for Three Levels of Iron Powder Content in Coating

The thermionic work function of the electrode material and, to a lesser extent, that of the materials being welded have a direct bearing on the efficiency of the energy transferred by a welding arc.

Electrical resistivity also plays an important role in these processes as a result of resistance heating of the electrode between the contact tube or electrode holder and the workpiece. Resistance heating of the electrode may be an important contribution to the total energy input to the weld zone.

To varying degrees, weld bead shape is dependent on the interfacial energy between the surrounding atmosphere and the molten metal. The surrounding atmosphere may consist either of a gas or a liquid flux. Elements in the surrounding medium may control the shape of the bead.

Another important material property that should be considered when determining the relative weldability of alloys is the rate of oxidation of the base metal. This rate is important in determining the degree of shielding required. A corollary to this is the relative stability of oxides that may be present. The specific heat and density of the shielding gases affect the heat of the arc and the shielding coverage.

THERMAL CONDUCTIVITY

Thermal conductivity decreases as the working temperature is increased in a manner analogous to the electrical conductivity values. Similarly, pure metals have the highest conductivity, and the addition of alloying elements tends to decrease the values of this property.

COEFFICIENT OF EXPANSION

The thermal coefficient of expansion of the materials being welded is important in analyzing distortion problems involved in welded assemblies. The same general considerations previously described for thermal conductivity and electrical resistivity are applicable to the coefficient of expansion.

IONIZATION POTENTIALS

In arc welding, the ease of arc initiation and the stability of the arc are related to the minimum ionization potential of the elements in the arc atmosphere. This atmosphere consists of flux materials and metal vapors as well as gases introduced externally for shielding purposes. It is believed that when helium and argon are used, the stability is achieved through the transitions from the metastable excited states to the ionized state. The ionization potentials of various metal vapors and gases are shown in Tables 2.6 and 2.7, respectively.

THERMIONIC WORK FUNCTION

The thermionic work function is the energy required for an electron to escape a solid surface. Since the ease of starting and maintaining an arc is exponentially related to the thermionic work function, representative values for a number of elements are listed in Table 2.8. Generally, the values do not appear to differ significantly on a proportional basis. However, work function affects electron emission rate exponentially. Thus, raising or lowering this value by even one eV significantly affects the arc characteristics.

ELECTRICAL RESISTIVITY

The importance of electrical resistivity to most welding processes cannot be overemphasized. Its role in resistance welding is obvious because the resistance of the materials being welded is directly related to the heat generated for a given welding current. Electrical resistivity also contributes to preheating the electrode in consumable electrode processes.

METAL OXIDES

The difficulty of transferring some alloying elements across the arc as well as the susceptibility to oxide inclusions in the weld metal are direct functions of the oxidation potential of the metal. The relative stability of several metal oxides and the reactivity of several metals are shown in Table 2.9.

Table 2.6
Ionization Potentials of Metal Vapors

Element	Electronvolts (eV)	Element	eV
Aluminum	5.986	Potassium	4.341
Barium	5.212	Lithium	5.392
Boron	8.298	Magnesium	7.646
Carbon	11.260	Molybdenum	7.099
Calcium	6.113	Nickel	7.635
Cobalt	7.860	Silicon	8.151
Chromium	6.766	Sodium	5.139
Cesium	3.894	Titanium	6.820
Copper	7.726	Tungsten	7.980
Iron	7.870		

Table 2.7
Ionization Potentials of Gases

Element or Compound	Electronvolts (eV)
Argon	15.760 (11.548)
Hydrogen	15.43 13.598
Helium	24.5876 (20.96430) (19.8198)
Nitrogen	15.58 14.534
Oxygen	12.07 13.618
Carbon Dioxide	13.77
Carbon Monoxide	14.1

Table 2.8
Electron Thermionic Work Functions

Element	Range, Electronvolts (eV)	Element	Range, eV
Aluminum	3.8–4.3	Magnesium	3.1–3.7
Barium	4.1–4.4	Manganese (α, β, or γ)	3.8–4.4
Barium Oxide	4.9–5.3	Molybdenum	4.0–4.8
Cerium	1.7–2.6	Neodymium	4.1–4.5
Cesium	1.0–1.6	Nickel	2.9–3.5
Cesium film or W	2.7–3.1	Palladium	4.5–5.3
Chromium	4.4–5.1	Platinum	4.9–5.7
Cobalt	3.9–4.7	Samarium	5.2–5.9
Niobium	1.8–2.1	Scandium	3.3–3.7
Copper	1.1–1.7	Silver	2.4–3.0
Europium	4.4–4.7	Strontium	2.1–2.7
Gadolinium	2.2–2.8	Titanium	3.8–4.5
Gold	4.2–4.7	Tungsten	4.1–4.4
Hafnium	2.9–3.3	Vanadium	4.3–5.3
Iron (α or γ)	3.5–4.0	Yttrium	2.9–3.3
Lanthanum	3.3–3.7	Zirconium	3.9–4.2

Table 2.9
Oxidation Potential of Metals and Metal Oxides

Relative Stability*	Relative Reactivity†
1. CaO	1. Aluminum
2. MgO	2. Magnesium
3. Al_2O_3	3. Cobalt and Titanium
4. TiO_2	4. Tungsten
5. SiO_2	5. Manganese
6. V_2O_3	6. Vanadium
7. MnO	7. Molybdenum
8. Cr_2O_3	8. Iron
9. WO_2 and MoO_2	9. Chromium
10. Fe_2O_3	

*Listed in decreasing order of stability.
†Listed in decreasing order of reactivity.

CONCLUSION

This chapter has provided basic information about the physics of various welding processes for the purpose of providing the practitioner a more fundamental knowledge with which to make decisions and determine applications. Due to the complexity of the physical processes in welding, it has been possible to provide only a cursory treatment of the subject. The reader is encouraged to consult the list of supplementary readings for in-depth coverage of specific topics of interest.

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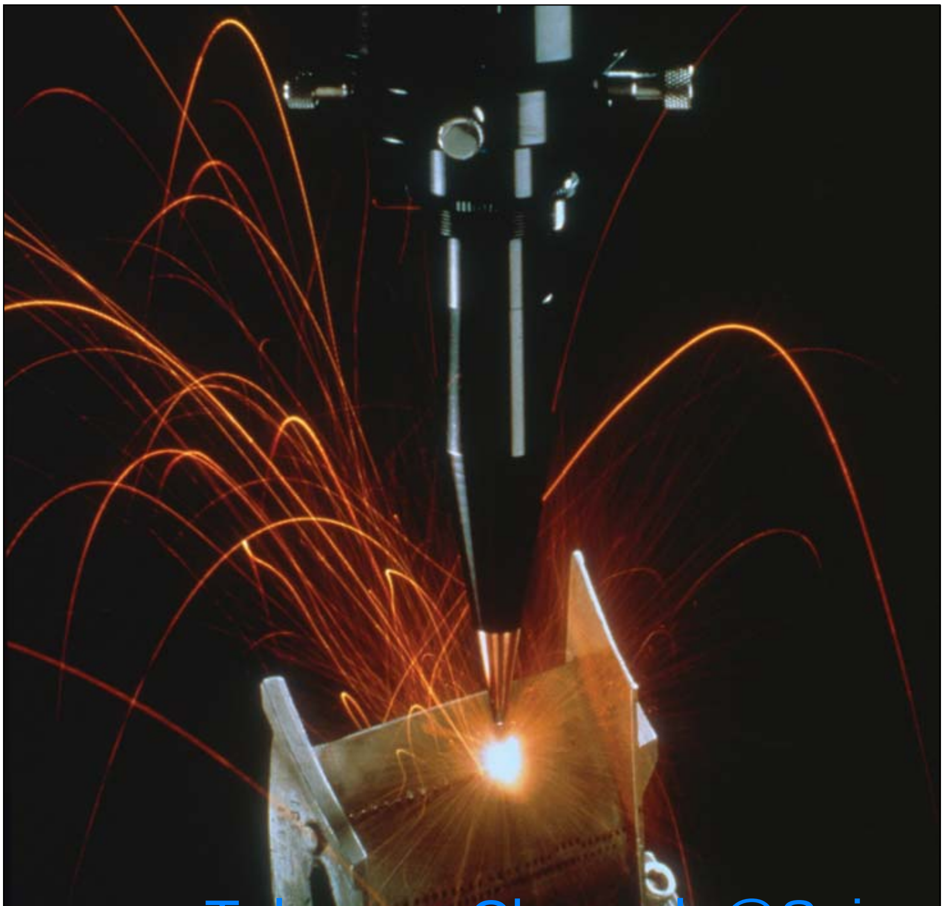
CHAPTER 3

HEAT FLOW IN WELDING



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The Ohio State University

Contents

CHAPTER 3

HEAT FLOW IN WELDING

INTRODUCTION

During fusion welding, the interaction between the base metal and the heat source leads to the rapid heating and melting and the vigorous circulation of molten metal. In the weld pool, the circulation of this molten metal is driven by buoyancy; the surface tension gradient, jet impingement, or friction; and, when electric current is used, electromagnetic forces. The resulting heat transfer and fluid flow affect the transient temperature distribution in the base material, the shape and size of the weld pool, and solidification behavior.

The variation of temperature with time, often referred to as the *thermal cycle*, affects microstructures, residual stresses, and the extent of the distortions in the weldment. On the surface of the weld pool, the temperature distribution affects the loss of alloying elements by evaporation as well as the absorption and desorption of hydrogen and other gases. Thus, the composition of the weldment is affected. In the interior of the weld pool, inclusions grow or dissolve, depending on the local temperature. The control of these temperature fields and cooling rates is essential to ensure sound welds with the desired fusion-zone geometry, chemical composition, and microstructure, as well as with low residual stress and distortion.

An understanding of heat transfer is important in the production of welds inasmuch as the properties of a weldment are controlled by its geometry and by the composition and structure of the materials being welded. The measurement of the temperature fields that form on the surface of the weld pool and in the weldment provides important information about heat transfer characteristics.

However, the measurement of surface temperatures during fusion welding is difficult. Although reliable techniques are being developed, such measurements are fairly complex and require specialized equipment. With respect to the measurement of temperature within the molten weld pool, no reliable technique currently exists. Temperature measurements in the solid regions commonly involve the placement of thermocouples, which are cumbersome and expensive, in holes drilled in the plates. Therefore, a recourse is to use quantitative calculations to gain insight into the phenomenon of heat transfer during fusion welding.

The fundamentals of heat transfer in fusion welding are examined in this chapter. The discussion focuses on arc, laser, and electron beam welding. In all welding, only a fraction of the energy dissipated by the heat source is actually absorbed by the base metal. Arc efficiency is an important parameter for the measurement of absorption efficiency in heat transfer during arc welding processes. In laser and electron beam welding, the proportion of energy absorbed by the metal is important. Thus, the factors responsible for the efficiency of energy absorption by the base metal are also discussed here.

In the weld pool, heat is transported by means of convection and conduction. Therefore, this chapter presents heat conduction calculations and several more advanced calculations that consider heat transfer by both conduction and convection in fusion welding. Because of its complexity, convective heat flow during welding cannot be solved analytically. As a result, the heat flow calculations made in the past were often limited to a simplified heat conduction calculation. Nonetheless, these heat conduction calculations provide a fairly simple and useful insight into fusion welding.

With the advent of high-speed computers, more realistic and accurate heat transfer calculations that take into consideration both conduction and convection can now be performed numerically. These complex calculations can accurately predict weld pool geometry, weld metal composition, and, in simple systems, weldment structure.

HEAT FLOW FUNDAMENTALS

The principal characteristics of the transfer of thermal energy from the welding arc to the workpiece and within the workpiece itself are reviewed in this section. These characteristics determine the maximum or peak temperatures in the weldment, the size and shape of the weld pool and the heat-affected zone, and the cooling rates of the weld metal and the heat-affected zone.

HEAT INPUT

The area of heat input is small relative to the overall dimensions of the workpiece. Three variables govern the input of heat to the workpiece regardless of whether the heat is applied on the weldment surface or internally to the weldment. These variables are (1) the magnitude of the rate of input energy (the product of the efficiency and the energy per unit time produced by the power source, usually expressed in watts), (2) the distribution of the heat input, and (3) the weld travel speed.

The expression *heat input* is used because not all of the welding energy enters the workpiece. Heat input is often characterized by the single variable H_{net}, which denotes the ratio of the arc power entering the workpiece to the weld travel speed. However, certain conditions require that the heat input rate and the weld speed be treated separately when describing the weld thermal cycle in the vicinity of the heat-affected zones.

ENERGY ABSORPTION

During welding, the workpiece absorbs only a portion of the total energy supplied by the heat source. The absorbed energy is responsible for the outcome of the welding, including the formation of the liquid pool, the establishment of the time-dependent temperature field throughout the entire weldment, and the structure and properties of the weldment.

The physical phenomena that influence the energy absorption in the workpiece are unique to each welding process. For a given power source, the extent to which the energy is absorbed by the workpiece depends on the nature of the material, the type of the heat source, and the parameters of the welding process. The efficiency of the heat source, η, is defined as the ratio of the energy absorbed by the workpiece to the energy supplied by the heat source, i.e., the fraction of energy transferred from the heat source to the workpiece.

Absorption Efficiency in Arc Welding Processes

For arc welding, the efficiency of the heat source is expressed as follows:[1]

$$\eta = 1 - \frac{q_e + (1-n)q_p + mq_w}{EI} \tag{3.1}$$

where

η = Arc efficiency, expressed as a fraction;
q_e = Rate of heat transfer to the electrode from the heat source, British thermal units per minute (Btu/min) (calories per second [cal/s]);
n = Proportion of the energy radiated and convected from the arc column per unit of time and transferred to the workpiece, expressed as a fraction;
q_p = Energy radiated and convected from the arc column per unit of time, Btu/min (cal/s);
m = Proportion of heat radiated away from the workpiece, expressed as a fraction;
q_w = Rate of heat absorbed by the workpiece, Btu/min (cal/s);
E = Voltage, volts (V); and
I = Welding current, amperes (A).

It should be noted that the second term on the right-hand side of the Equation (3.1) is dimensionless. If the units of the numerator and the denominator are Btu/min and volt-ampere (i.e., watts), respectively, the second term in the right-hand side should be multiplied by 17.58 to convert Btu/min to watts.

For a consumable electrode, the heat loss from the electrode can often be ignored. In such a situation, the amount of energy transferred to the electrode is eventually absorbed by the workpiece. Thus, Equation (3.1) can be simplified as follows:[2]

$$\eta = 1 - \frac{(1-n)q_p + mq_w}{EI} \tag{3.2}$$

where

η = Arc efficiency, expressed as a fraction;
n = Proportion of the energy radiated and convected from the arc column per unit of time and transferred to the workpiece, expressed as a fraction;
q_p = Energy radiated and convected from the arc column per unit of time, Btu/min (cal/s);
m = Proportion of heat radiated away from the workpiece, expressed as a fraction;
q_w = Rate of heat absorbed by the workpiece, Btu/min (cal/s);
E = Voltage, V; and
I = Welding current, A.

1. Lancaster, J. F. 1986, *The Physics of Welding*, 2nd ed., Oxford: Pergamon Press, p. 163.

2. See Reference 1.

Equations (3.1) and (3.2) are useful in explaining the manner in which the various types of heat loss affect arc efficiency. However, it is difficult to estimate the heat loss terms q_e, q_p, and q_w accurately from theoretical considerations. For purposes of practicality, arc efficiency is determined experimentally by performing an appropriate calorimetric or other measurement of the heat received by the workpiece for a given welding condition.[3] Arc efficiencies in the range of 20% to over 95% have been reported.[4]

Experimentally measured heat-source efficiencies are available for various welding processes.[5] The arc efficiencies, η, for three welding processes are summarized in Figure 3.1. It can be observed that the arc efficiency is lowest in gas tungsten arc welding (GTAW), intermediate in the shielded metal arc welding (SMAW) and gas metal arc welding and (GMAW), and highest in the submerged arc welding (SAW) process.

As a rule, arc efficiency is higher for consumable-electrode processes than for nonconsumable-electrode processes. In gas tungsten arc welding, for example, the electrode is nonconsumable, resulting in substantial heat loss from the arc to the surrounding environment. It should be noted, however, that arc efficiencies between 60% and 90% have been reported for the GTAW process, as illustrated in Figure 3.2. Arc efficiencies in similar ranges have also been reported elsewhere.[6]

In consumable-electrode welding processes such as gas metal arc welding, shielded metal arc welding, and submerged arc welding, almost all of the energy consumed in the heating and melting of the electrode is transferred to the workpiece through the liquid metal droplets, resulting in higher efficiencies. In the submerged arc welding process, arc efficiency is further increased because the arc is covered by an insulating blanket of molten and granular flux, thus minimizing heat loss to the surrounding area.

Arc efficiency can be measured experimentally using a calorimeter in the form of a round, square, or rectangular pipe,[7] as shown in Figure 3.3(A).

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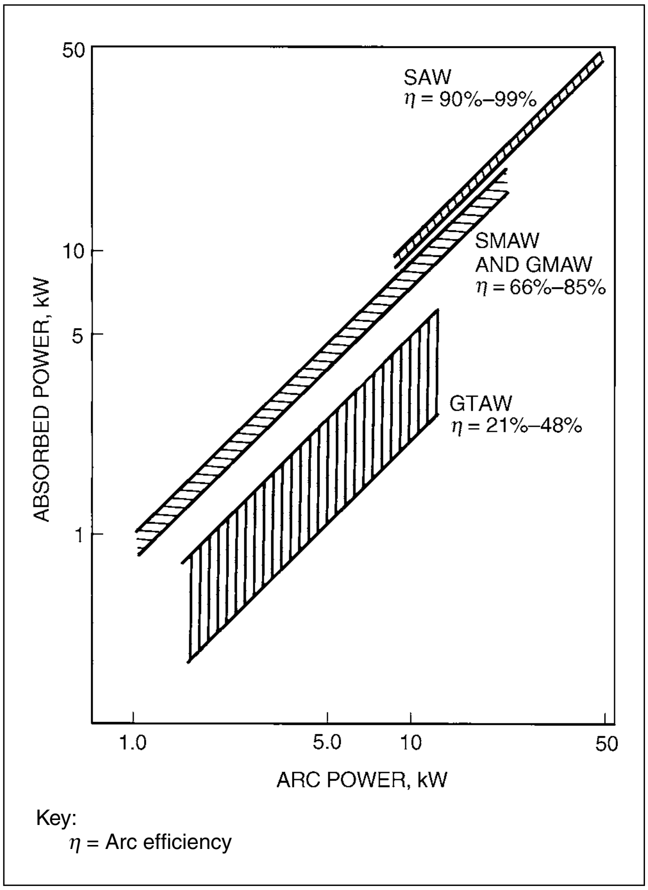

Source: Christensen, N., V. L. Davies, and K. Gjermundsen, 1965, Distribution of Temperature in Arc Welding, *British Welding Journal* 12(2): 54–75.

Figure 3.1—Measured Arc Efficiencies in Various Welding Processes

The arc efficiency, η, is determined using the following equation:

$$\int_0^\infty WC_w(T_{\text{out}} - T_{\text{in}})dt = \eta EIt_{\text{weld}} \tag{3.3}$$

where

W = Mass flow rate of water, pounds per minute (lb/min) (grams per second [g/s]);
C_w = Specific heat of water, British thermal unit per pound per degree Fahrenheit (Btu/[lb °F]) (calorie per gram per degree Celsius (cal/[g °C]);
T_{out} = Outlet water temperature, °F (°C);
T_{in} = Inlet water temperature, °F (°C);
I = Welding current, A;
dt = Time increment, min (s);

3. Smartt, H. B., J. A. Stewart, and C. J. Einerson, 1985, *Heat Transfer in Gas Tungsten Arc Welding,* American Society for Metals (ASM) Metals/Materials Technology Series Paper No. 8511-011, Metals Park, Ohio: American Society for Metals; Giedt W. H., L. N. Tallerico, and P. W. Fuerschbach, 1989, GTA Welding Efficiency: Calorimetric and Temperature Field Measurements, *Welding Journal* 61(4): 97-s–102-s; Fuerschbach, P. W., 1994, Measurement and Prediction of Energy Transfer Efficiency in Laser Beam Welding. Personal communication, Sandia National Laboratory, Albuquerque, New Mexico.
4. Kou, S., 1987, *Welding Metallurgy,* New York: John Wiley and Sons.
5. See Reference 4.
6. Ghent, H. W., D. W. Roberts, C. E. Hermance, H. W. Kerr, and A. B. Strong, 1980, *Arc Physics and Weld Pool Behavior,* London: The Welding Institute; Kou, S., and Y. Le, 1984, Heat Flow during the Autogenous GTA Welding of Pipes, *Metallurgical Transactions A* 15A: 1165.
7. Kou, S., and Y. Le, 1984, Heat Flow during the Autogenous GTA Welding of Pipes, *Metallurgical Transactions A* 15A: 1165.

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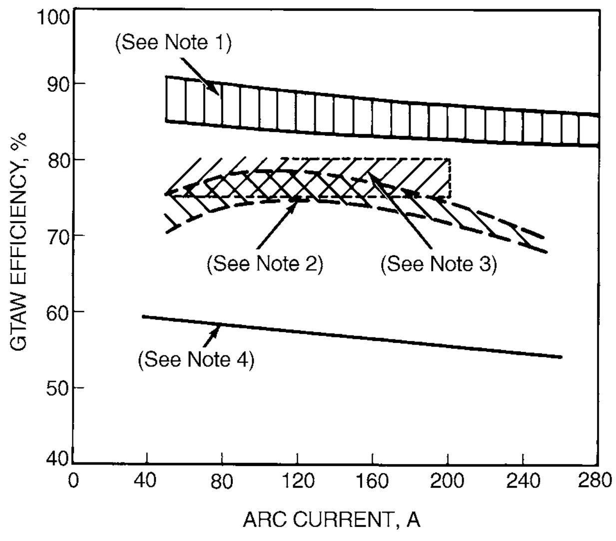

Notes:
1. Data from Tsai, N. S., and T. W. Eagar, 1985, Distribution of Heat and Current Fluxes in Gas Tungsten Arcs, *Metallurgical Transactions B* 16B(12): 841–846.
2. Data from Smartt, H. B., J. A. Stewart, and C. J. Einerson, 1985, *Heat Transfer in Gas Tungsten Arc Welding*, American Society for Metals (ASM) Metals/Materials Technology Series Paper No. 8511-011, Metals Park, Ohio: American Society for Metals.
3. Data from Glickstein, S. S., and E. Friedman, 1984, Weld Modeling Applications, *Welding Journal* 63(9): 38–42.
4. Data from Eagar, T. W., and N. S. Tsai, 1983, Temperature Fields Produced by Traveling Distributed Heat Sources, *Welding Journal* 62(12): 346-s–355-s.

Figure 3.2—Comparison of GTAW Arc Efficiencies from Data Reported by Several Investigators

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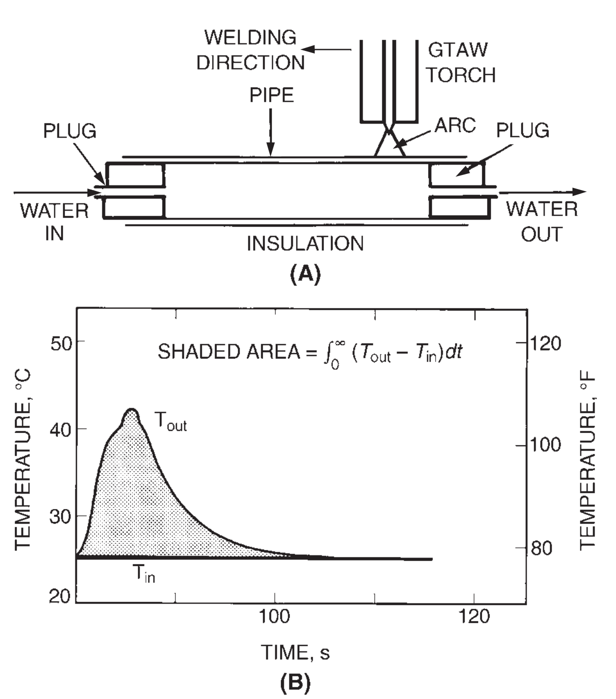


Key:
T_{out} = Outlet water temperature, °F (°C)
T_{in} = Inlet water temperature, °F (°C)
t = Time increment, min (s)

Source: Adapted from Kou, S., and Y. Le, 1984, Heat Flow during the Autogenous GTA Welding of Pipes, *Metallurgical Transactions A* 15A: 1165.

Figure 3.3—Measurement of Arc Efficiency in GTAW: (A) Calorimeter and (B) Temperature Variations

η = Arc efficiency, expressed as a fraction;
E = Welding arc voltage, V; and
t_{weld} = Welding time, min (s).

Both sides of Equation (3.3) should have the same units to achieve dimensional consistency. If the units on the right-hand side and the left-hand side are Btu and volt-ampere-minute (i.e., watt-min) respectively, the right-hand side should be multiplied by 0.057 to convert watt-min to Btu.

In the water temperature range investigated in the studies conducted, C_w and W can be considered constant. Thus, Equation (3.3) becomes the following:

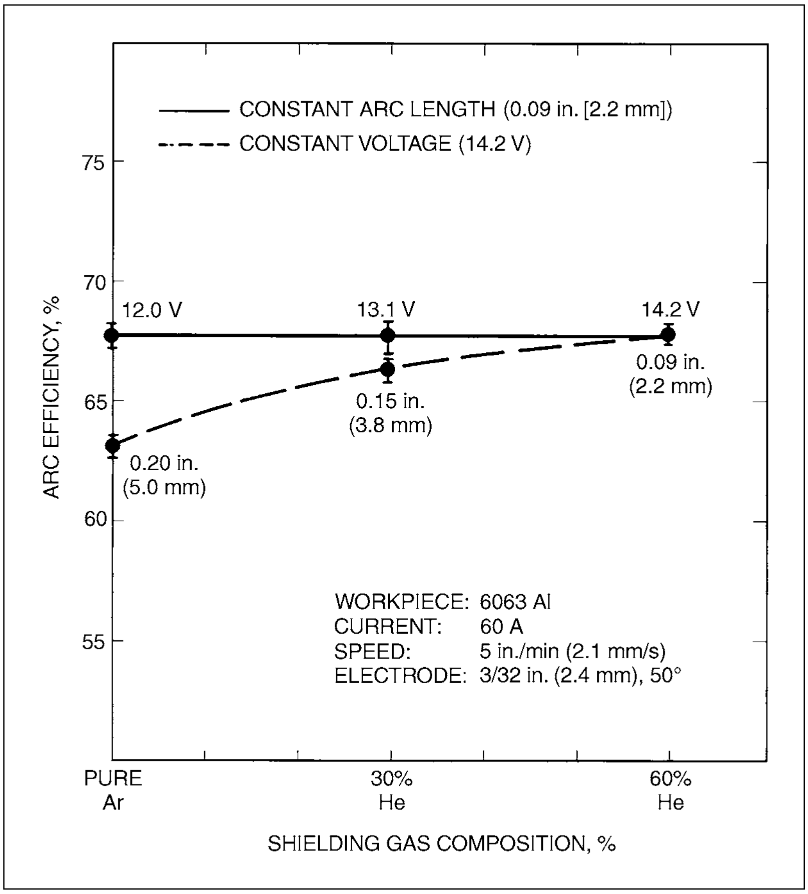
$$\int_0^\infty (T_{out} - T_{in})\,dt = \frac{\eta E I t_{weld}}{W C_w} \qquad (3.4)$$

where

T_{out} = Outlet water temperature, °F (°C);
T_{in} = Inlet water temperature, °F (°C);
dt = Time increment, min (s);
η = Arc efficiency, expressed as a fraction;
E = Welding arc voltage, V;
I = Welding current, A;
t_{weld} = Welding time, min (s);
W = Mass flow rate of water, lb/min (g/s); and
C_w = Specific heat of water, Btu/(lb° F) (cal/[g °C]).

The left-hand side of this equation is represented by the area between the two curves, T_{out} and T_{in}, which is illustrated in Figure 3.3(B).

In gas tungsten arc welding, arc efficiency has been reported to be much lower when alternating current (ac)



Source: Adapted from Kou, S., 1987, *Welding Metallurgy,* New York: John Wiley and Sons.

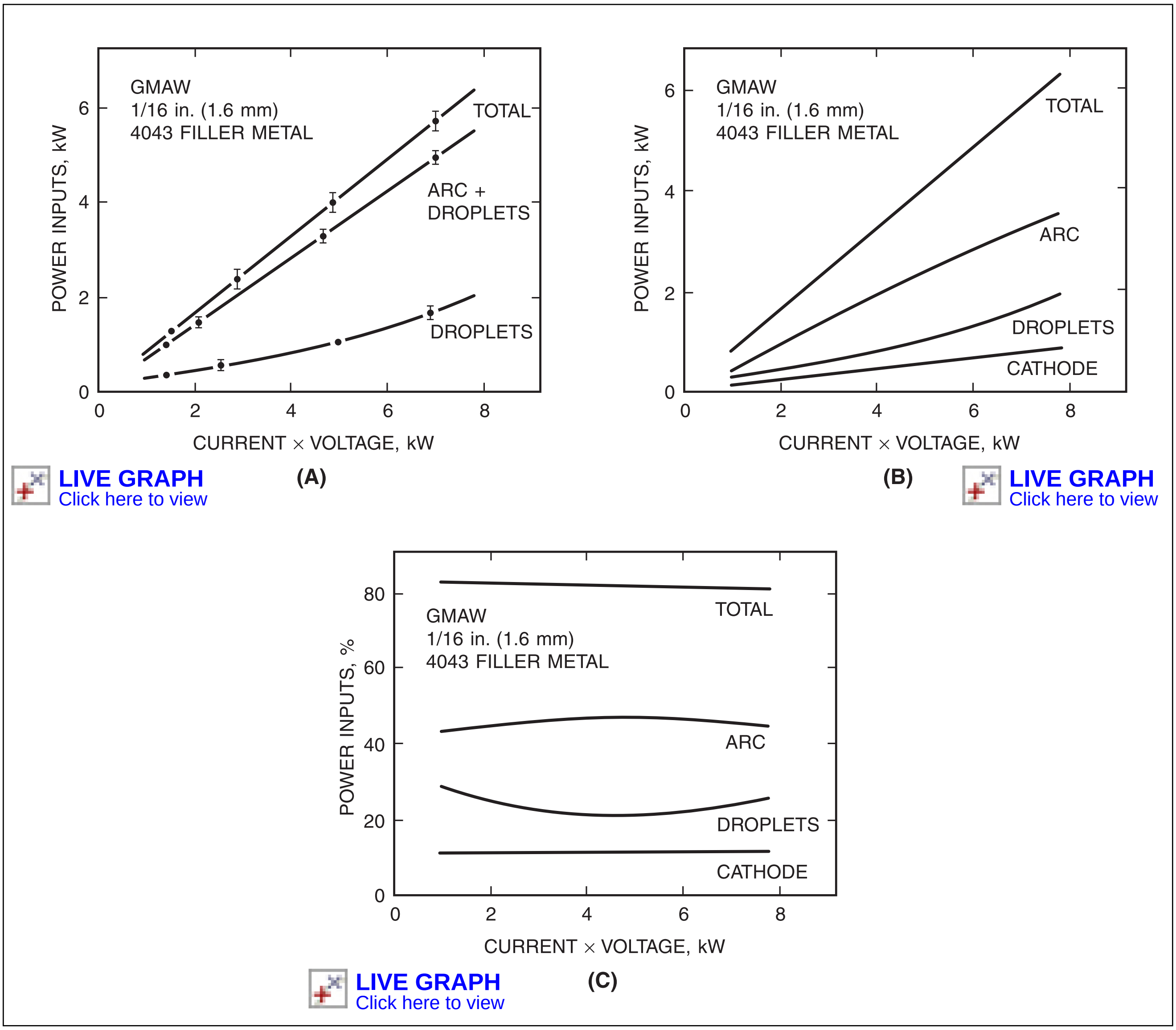
Figure 3.4—Results of Arc Efficiency Measurement in GTAW

is used rather than direct current electrode negative (DCEN).[8] As shown in Figure 3.4, arc efficiency increases at a constant welding current and voltage as the arc gap decreases from 0.2 inches (in.) to 0.09 in. (5 millimeters [mm] to 2.2 mm).[9] If the arc gap remains constant and the voltage is increased from 12 volts (V) to 14 V at constant current, the efficiency remains unchanged.

By using a combination of calorimeters and special electrode and workpiece arrangements, the heat-source efficiency in gas metal arc welding has been measured so that the relative contributions from the arc, droplets, and cathode heating could be determined.[10] The experimental results are shown in Figure 3.5. The shielding gas used was argon (Ar). Figure 3.5(A) shows the gas metal arc welding of aluminum using a common 4043 aluminum filler wire. The variables of interest are the measured total power input, the combined power input due to the arc and the filler-wire droplets, and the power input from the droplets alone. From these, the individual contributions can be determined, as shown in Figures 3.5(B) and (C).

8. Ghent, H. W., D. W. Roberts, C. E. Hermance, H. W. Kerr, and A. B. Strong, 1980, *Arc Physics and Weld Pool Behavior,* London: The Welding Institute; Smartt, H. B., J. A. Stewart, and C. J. Einerson, 1985, *Heat Transfer in Gas Tungsten Arc Welding,* American Society for Metals (ASM) Metals/Materials Technology Series Paper No. 8511-011, Metals Park, Ohio: American Society for Metals.
9. See Reference 3.

10. Lu, M. J., and S. Kou, 1989a, Power Inputs in Gas Metal Arc Welding of Aluminum—Part 1, Droplet Heat Content, *Welding Journal* 68: 382-s–388-s; Lu, M. J., and S. Kou, 1989b, Power Inputs in Gas Metal Arc Welding of Aluminum—Part 2. Arc and Cathode Heating, *Welding Journal* 68: 452-s–388-s.



Sources: Adapted from Lu, M. J., and S. Kou, 1989a, Power Inputs in Gas Metal Arc Welding of Aluminum—Part 1. Droplet Heat Content, *Welding Journal* 68: 382-s–388-s; Lu, M. J., and S. Kou, 1989b, Power Inputs in Gas Metal Arc Welding of Aluminum—Part 2, Arc and Cathode Heating, *Welding Journal* 68: 452-s–456-s.

Figure 3.5—Power Inputs in the Gas Metal Arc Welding of Aluminum: (A) Measured Inputs, (B) Total and Individual Inputs, and (C) Total and Individual Efficiencies

Absorption Efficiency in Laser and Electron Beam Welding

During laser welding, the absorption of the laser beam by the workpiece is affected by several factors, including the wavelength of the laser, the nature of the surface, joint geometry, and the size and nature of the plasma present above the weld pool. The absorption of infrared energy by metals depends largely upon conductive absorption by free electrons. Therefore, for clean metal surfaces, the absorptivity can be calculated from the knowledge of the electrical resistivity of the substrate.

In an analysis of experimental data, Arata and Miyamoto demonstrated that the absorptivity of various flat, polished surfaces is a linear function of the square root of the electrical resistivity of the respective metals.[11] Bramson related the absorptivity to the substrate resistivity and the wavelength of the laser radiation by means of the following relationship:[12]

$$\eta_l = 0.365\left[\frac{r}{\lambda}\right]^{1/2} - 0.0667\left[\frac{r}{\lambda}\right] + 0.006\left[\frac{r}{\lambda}\right]^{3/2} \qquad (3.5)$$

where

η_l = Absorptivity at a temperature, T, fraction;
r = Resistivity, ohms-inch (Ω-in.) (Ω-cm); and
λ = Wavelength, in. (cm).

Such calculations are accurate when metal surfaces are clean and a plasma plume is not affecting the absorption of the laser beam. All metal surfaces are highly reflective to the infrared radiation of a carbon dioxide laser at room temperature. Thus, the transfer of energy from the laser beam to the workpiece can be inefficient.

Theoretically, the estimated absorption coefficients obtained from Equation (3.5) are valid for flat surfaces. When the weld pool forms, the liquid surface may deform because of the motion of the liquid and the inherent instability of the flow, or both. In addition, most alloy surfaces have thin layers of oxides, which can significantly affect the absorption coefficient. When the power density is high, material can vaporize rapidly from the molten pool, and a cavity the shape of a keyhole can form in the material because of the recoil force of the vapor on the liquid metal. When the keyhole forms, the energy absorption efficiency can improve dramatically to a value much higher than that predicted by Equation (3.5), owing to multiple reflections of the beam in the cavity.

When plasma forms near the weld pool, a part of the energy from the laser beam can be absorbed by the plasma before the beam reaches the material. Thus, it is important to know how much of the laser energy is actually absorbed by the plasma. Theoretical treatments are available for simple systems.[13] A free electron traveling through the electric field in plasma can absorb a photon and acquire additional kinetic energy. The free-free transition involving photon absorption is referred to as *inverse bremsstrahlung*. The absorption of light can also occur when an electron passes through the field of a neutral atom. In contrast to the field of an ion, the field of a neutral atom decreases rapidly with distance. Therefore, the electron must pass very close to the atom to ensure the absorption of photons. For this reason, the absorption effect is significantly more pronounced in plasma than in a molecular gas.

Assuming that the electron velocities obey a Maxwell distribution, ZelDovich and Raizer obtained the following bremsstrahlung absorption coefficient:[14]

$$k_v = 3.69 \times 10^8 \frac{Z^2}{v^3\sqrt{T}} N_+ N_e \qquad (3.6)$$

where

k_v = Absorption coefficient for energy absorption by plasma, cm^{-1};
Z = Ionic charge in multiples of unit electronic change;
v = Frequency, s^{-1};
T = Electron temperature, K;
N_+ = Number density of positively charged ions, cm^{-3}; and
N_e = Number density of positively charged electrons, cm^{-3}.

It should be noted that the units used in Equation (3.6) are not those commonly used in this volume. The units listed below Equation (3.6) are consistent with the coefficient 3.69×10^8 indicated by ZelDovich and Raizer.[15]

The quantitative calculation of the bremsstrahlung absorption coefficient is a highly complex task since it requires the estimation of the local properties of the plasma during laser welding. Because of the difficulties inherent to the accurate theoretical prediction of the absorption coefficient, experimentally determined values should be used when such data are available.[16]

Rockstroh and Mazumder[17] have conducted aluminum welding experiments using argon shielding gas. They found that the extent of inverse bremsstrahlung absorption was approximately 20% and 31% for welding with 5 kilowatt (kW) and 7 kW laser powers, respectively. For the welding of steels with low-power carbon dioxide lasers, overall bremsstrahlung absorp-

11. Arata, Y., and I. Miyamoto, 1978, Laser Welding, *Technocrat* 11(5): 33.
12. Bramson, M. A., 1968, *Infrared Radiation: A Handbook for Applications,* New York: Plenum Press.
13. ZelDovich Y. B., and Y. P. Raizer, 1966, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena,* New York: Academic Press.

14. See Reference 13.
15. See Reference 13.
16. Huntington, C. A., and T. W. Eagar, 1983, Laser Welding of Aluminum and Aluminum Alloys, *Welding Journal* 62(4): 105-s–107-s; Khan, P. A., and T. DebRoy, 1985, Laser Beam Welding of High-Manganese Stainless Steels—Examination of Alloy Element Loss and Microstructure Changes, *Metallurgical Transactions B* 16B: 853–856; Fuerschbach, P. W., 1994, Measurement and Prediction of Energy Transfer Efficiency in Laser Beam Welding, Personal communication, Sandia National Laboratory, Albuquerque, New Mexico.
17. Rockstroh, T. D., and J. Mazumder, 1987, Spectroscopic Studies of Plasma during CW Laser Materials Interaction, *Journal of Applied Physics* 61(3): 917–923.

tion efficiencies of less than 10% have been reported by Collur[18] and Miller.[19] The available data indicate that (1) the absorption of beams by plasma is significant under welding conditions and (2) absorption must be considered in a quantitative analysis of heat transfer in welding processes.

The efficiency of laser beam welding can range from very low, such as that achieved with polished aluminum or copper, to very high, as in deep penetration keyhole welding or in the welding of materials with low reflectivity. Efficiency can be improved in some cases by coating the surface of the workpiece with thin layers of graphite and zinc phosphate to enhance the absorption of the beam's energy. The effect of the surface layers on the properties of the weld should be investigated before this technique is used in production, however.

Because weld keyholes tend to trap most of the energy from the heat source, the efficiency of the heat source can reach approximately 70% in keyhole laser beam welding. Similarly, the efficiency can be between 80% to 90% in keyhole electron beam welding.

QUANTITATIVE CALCULATION OF HEAT TRANSFER IN FUSION WELDING

The transfer of heat in the weldment is governed primarily by the time-dependent transport of heat by both conduction and convection, which is expressed by the following equation regarding the conservation of energy:[20]

$$\rho \frac{\partial}{\partial t}[CT] + \rho v_x \frac{\partial}{\partial x}[CT] + \rho v_y \frac{\partial}{\partial y}[CT] + \rho v_z \frac{\partial}{\partial z}[CT] = \frac{\partial}{\partial x}[k\frac{\partial T}{\partial x}] + \frac{\partial}{\partial y}[k\frac{\partial T}{\partial y}] + \frac{\partial}{\partial z}[k\frac{\partial T}{\partial z}] + S \quad (3.7)$$

where

ρ = Density of the metal, lb/in.^{3} (g/cm^3);

t = Time, min (s);

C = Specific heat of the metal, Btu/(lb °F) (cal/[g °C]);

T = Temperature in the weldment; °F (°C);

v_x = Velocity component in the x-direction, in/min (cm/s);

x = Coordinate in the welding direction, in. (cm);

v_y = Velocity component in the y-direction, in./min (cm/s);

y = Coordinate transverse to the weld, in. (cm);

v_z = Velocity component in the z-directions, in./min (cm/s);

z = Coordinate normal to the weldment surface and pointing into the weldment, in. (cm);

k = Thermal conductivity of the metal, Btu/(min in. °F) (cal/[s cm °C]); and

S = Rate of internal volumetric heat generation, Btu/(in.^{3} min) (cal/[cm^3 s]).

The coordinate system (x, y, z) is shown in Figure 3.6. Its origin coincides with the center of the heat source at the surface of the workpiece. The heat source travels at a constant speed, U, in the same direction as the x-axis while the workpiece remains stationary. Mathematically, this is equivalent to the case in which the heat source remains stationary while the workpiece travels at a constant speed, U, in the x-direction.

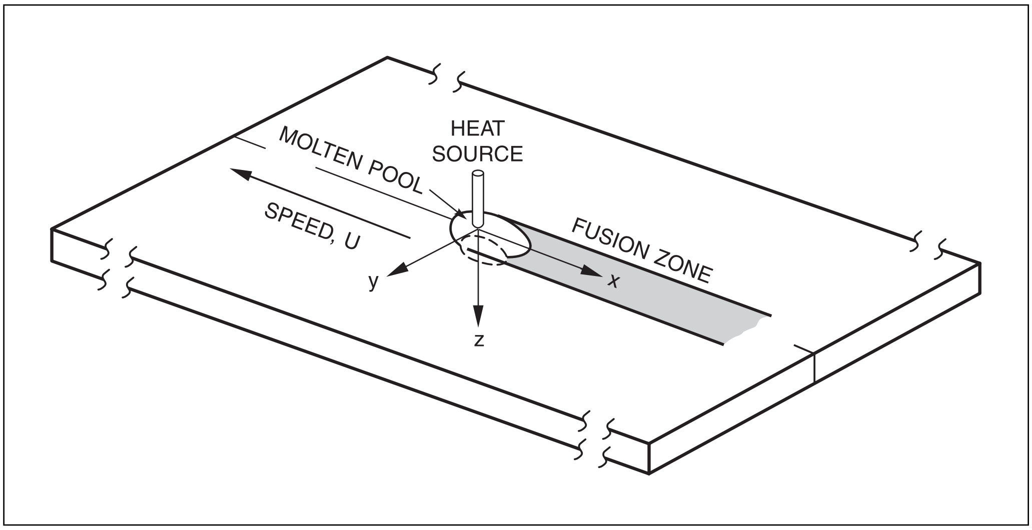
The first term on the left side of Equation (3.7) is transient, which accounts for the change in the heat content of the workpiece. The remaining terms on the left represent convective heat transfer. The first three terms on the right represent heat transfer by conduction, while S denotes the rate of internal volumetric heat generation. This variable is important when the welding process involves an input of energy below the surface of the workpiece. Examples of such processes are submerged arc welding, heat transfer by droplet in gas metal arc welding, and laser and electron beam welding.

The boundary conditions for the solution of Equation (3.7) may specify the temperature at various locations on the surface of the workpiece. For a large workpiece, the surface temperatures distant from the heat source can be taken as the room temperature. However, near the heat source, the surface temperatures are much higher and unknown in most situations.

DEPOSITION OF HEAT IN ARC WELDING

For the arc welding processes, the deposition of heat can be characterized as a distributed heat flux on the weldment surface. Assuming that the heat from the welding arc is applied at any given instant of time as a

18. Collur, M. M., 1988, Alloying Element Vaporization and Emission Spectroscopy of Plasma during Laser Welding of Stainless Steels, Ph.D. diss., The Pennsylvania State University.
19. Miller, R., 1989, Absorption of Laser Beam by Plasma during Laser Welding of Stainless Steel, Master's thesis, The Pennsylvania State University.
20. Kou, S., 1996, *Transport Phenomena in Materials Processing*, New York: John Wiley and Sons.



Source: Adapted from Kou, S., and Y. Le, 1984, Heat Flow during the Autogenous GTA Welding of Pipes, *Metallurgical Transactions A* 15A: 1165.

Figure 3.6—Coordinate System for Heat Flow Analysis in Welding

normally distributed heat flux, the rate of the heat deposition is expressed by the following equation:

$$q(x,y) = \frac{3EI\eta}{\pi\bar{r}^2}\exp\{-3(x^2+y^2)/\bar{r}^2\} \qquad (3.8)$$

where

- q = Heat flux, Btu/(in.^{2} min) (cal/[cm^2 s]);
- x = Coordinate in the welding direction, in. (cm);
- y = Coordinate transverse to the weld, in. (cm);
- E = Welding voltage, V;
- I = Welding current, A;
- η = Arc efficiency;
- π = 3.1416; and
- $\bar{r}$ = Characteristic radial dimensional distribution parameter that defines the region in which 95% of the heat flux is deposited,[21] in. (cm).

Both sides of Equation (3.8) should have the same units. If the units on the right-hand side and the left-hand side are Btu/(in.^{2} min) and volt-ampere/in.^{2} (i.e., watt/in.^{2}), respectively, the right-hand side should be multiplied by 0.057 to convert watt/in.^{2} to Btu (in.^{2} min).

This type of thermal energy density distribution is often used as an approximation,[22] as illustrated in Figure 3.7. The broken curve is the Gaussian power distribution according to Equation (3.8). The radial distance, r, is defined as $r^2 = x^2 + y^2$.

DISSIPATION OF WELDING HEAT

Welding heat is lost to the surrounding atmosphere by radiation and convection. Radiation losses are proportional to the fourth power of the absolute temperature, T^4, of the metal surface. The extent of the convective loss depends on the nature of the shielding gas, its flow rate, and its configuration system. The boundary condition for heat loss from the weldment surface is given by the following:

$$k\frac{\partial T}{\partial n} = q_n = h_c(T - T_a) + \varepsilon\sigma(T^4 - T_a^4) \qquad (3.9)$$

where

- k = Thermal conductivity, Btu/(min in. °F) (cal/[s cm °C]);

21. Friedman, E., 1975, Thermomechanical Analysis of the Welding Process Using the Finite Element Method, *Transactions of ASME* 97(3): 206–213.

22. Tsai, N. S., and T. W. Eagar, 1985, Distribution of Heat and Current Fluxes in Gas Tungsten Arcs, *Metallurgical Transactions B* 16B(12): 841–846.

LIVE GRAPH
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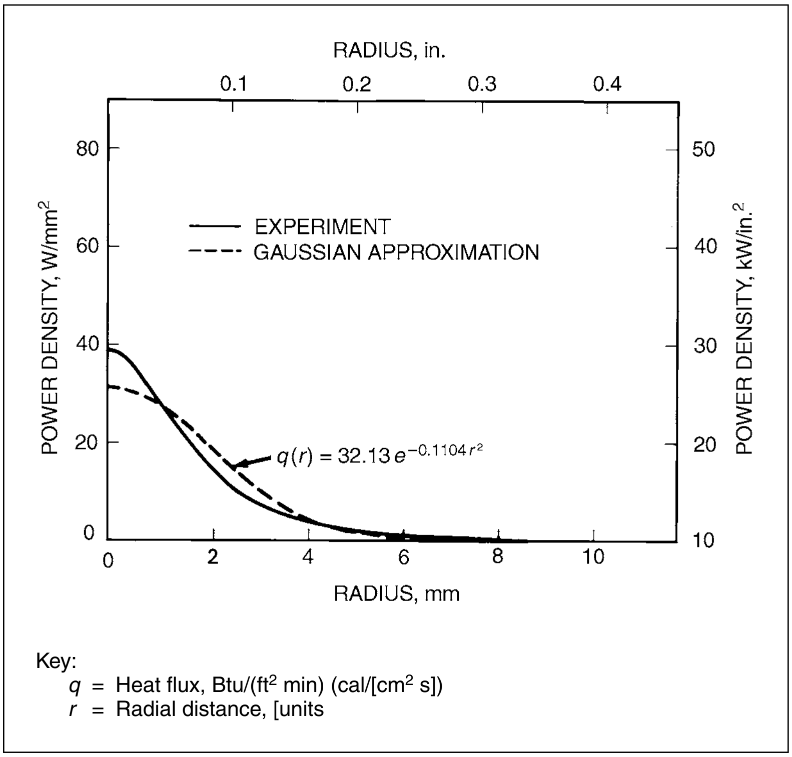


Source: Adapted from Tsai, N. S., and T. W. Eagar, 1985, Distribution of Heat and Current Fluxes in Gas Tungsten Arcs, *Metallurgical Transactions B* 16B(12): 841–846.

Figure 3.7—Power Density Distribution in a Gas Tungsten Arc

T = Local temperature at the surface of the workpiece, °F (°C);
n = Distance normal to surface, in. (cm);
q_n = Heat flux normal to the surface, Btu/(in.^{2} min) (cal/[cm^2 s]);
h_c = Convective heat transfer coefficient, Btu/(in.^{2} min °F) (cal/[cm^2 s °C]);
T_a = Surrounding temperature, °F (°C);
ε = Emissivity of the workpiece; and
σ = Stefan-Boltzmann constant, 1.981×10^{-13} Btu/(in.^{2} min °R^4) (1.355×10^{-12} cal/[cm^2 s K^4]).

The first term on the right side of Equation (3.9) represents heat transfer by convection, while the second term represents heat transfer by radiation. The calculation of the second term on the right-hand side of Equation (3.9) requires special care in selecting units of temperature, which must be expressed in an absolute temperature scale. In this term, temperatures T and T_a must be expressed in degrees Rankine (°F + 460) or Kelvin (°C + 273).

CONDUCTION OF HEAT DURING FUSION WELDING

A rigorous solution of the complete heat flow equation considering heat transfer by both conduction and convection is complex. As a first step, it is often useful to discuss a simplified solution considering only conduction heat flow. This simplification is attractive since analytical solutions can be obtained for the heat conduction equation in many situations, and these solutions can provide interesting insight about the fusion welding processes. For example, calculated temperature profiles are useful in determining weld pool shape and size, cooling rates, the size of the heat-affected zone, and the resulting weldment structure.

Subsequent to a discussion of heat transfer by conduction, the relative importance of heat transfer by conduction and convection is examined, and the consequences of convective heat transfer in the fusion welding processes are indicated.

During fusion welding, temperature gradients exist throughout the thickness of the weld as well as in directions parallel and transverse to the welding direction. Therefore, the heat flow pattern resulting from a moving heat source is three-dimensional. However, this heat flow pattern can be simplified somewhat by assuming the following:

1. Energy from the welding heat source is applied at a uniform rate,
2. The heat source moves at a constant speed on a straight path relative to the workpiece,
3. The cross section of the weld joint is constant, and
4. End effects resulting from initiation and termination of the weld are neglected.

If the thermal cycle in the proximity of the weld metal and heat-affected zone is not of interest, the heat input distribution is unimportant, and the heat input can be treated as a concentrated heat source. The heat input and the weld speed are then sufficient to determine the thermal cycle.

Rosenthal's analytical solution for quasi-steady two-dimensional heat flow in a very wide workpiece due to a moving point heat source is as follows:[23]

$$\frac{2\pi(T-T_o)k_s b}{Q} = e^{-\frac{U(x-Ut)}{2\alpha_s}} k_o\left(\frac{Ur}{2\alpha_s}\right) \tag{3.10}$$

where

π = 3.1416;
T = Temperature, °F (°C);
T_o = Workpiece temperature before welding, °F (°C);
k_s = Thermal conductivity of the solid, Btu/(min in. °F) (cal/([s cm °C]);
b = Thickness of workpiece, in. (cm);
Q = Heat input to the workpiece, Btu/min (cal/s);
e = 2.718;
U = Welding speed, in/min (cm/s);
x = Distance along the direction of welding, in. (cm);
t = Time, min (s);
k_o = Modified Bessel function of the second kind and zero order;
r = Radial distance from the origin, $(x^2 + y^2)^{1/2}$, in. (cm), where y equals the distance in the plate surface perpendicular to the x-direction, in. (cm); and
α_s = Thermal diffusivity of the solid, in.^{2}/min (cm^2/s).

Similarly, Rosenthal's analytical solution for quasi-steady three-dimensional heat flow in a semi-infinite (very thick and large) workpiece due to a moving point heat source is as follows:[24]

$$\frac{2\pi(T-T_o)k_s R}{Q} = e^{-\frac{U(x-Ut+R)}{2\alpha_s}} \tag{3.11}$$

where R equals the radial distance from the origin, $(x^2 + y^2 + z^2)^{1/2}$, in. (cm), and the remaining variables are defined above. In Equations (3.10) and (3.11), the origin of the coordinates is the location of the heat source.

Examples of results based on Rosenthal's three-dimensional heat flow equation, Equation (3.11), are presented in Figures 3.8 and 3.9.[25] As shown in Figures 3.7 and 3.8, the weld pool becomes more elongated when the welding speed and the heat input are increased, which is qualitatively consistent with experimental observations.

As shown in Figures 3.8(A) and 3.9(A), the temperature at the location of the point heat source approaches infinity due to singularity associated with Rosenthal's point heat source assumption. To overcome this problem and improve the accuracy of the calculation of heat flow, it is desirable to relax this and other assumptions. Greater accuracy can be achieved in many cases if variable thermal properties of the workpiece and the heat of fusion of the weld metal are considered and the heat loss from the workpiece to the surroundings is taken into account. Moreover, fluid flow in the weld pool should also be considered because heat transfer occurs not only by conduction but also by convection.

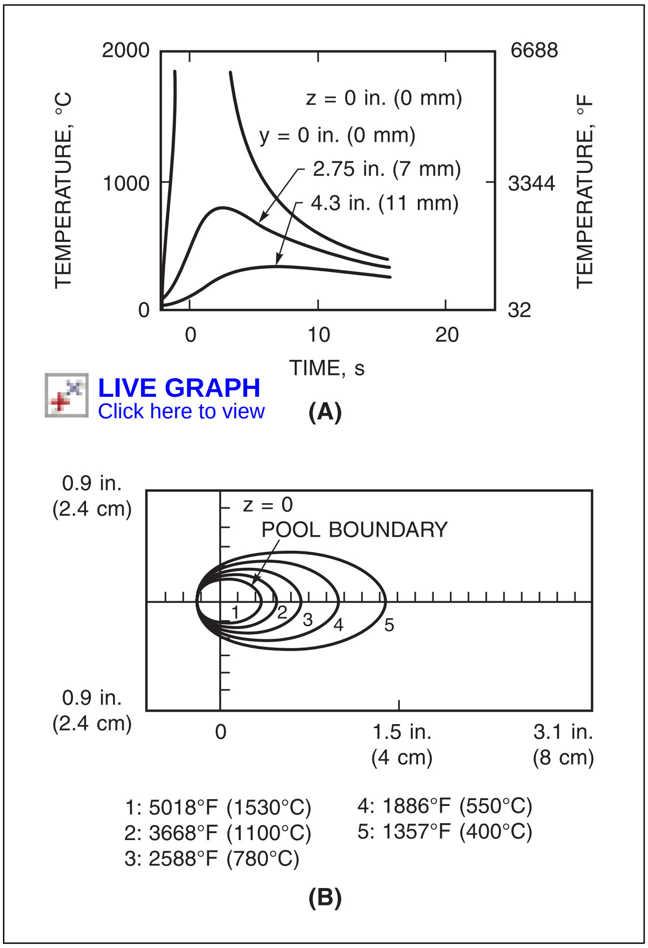
The rate of energy loss from the weld zone is a direct function of the heat conductivity and temperature gradient and an inverse function of the heat capacity. The difference in the thermal properties of shielding gases such as argon and helium can also have an important effect on the cooling rate.

PRACTICAL APPLICATIONS OF HEAT CONDUCTION EQUATIONS

As the rigorous solutions to heat flow in fusion welding are complex, computers are required for their computation. However, for conditions that result in approximately semicircular or oval weld bead cross sections, the equations can be simplified by assuming a point heat source. Under this assumption, the ratio of the welding energy entering the base metal per unit time to the weld travel speed, H_{net}, becomes a principal variable in the heat flow equations.

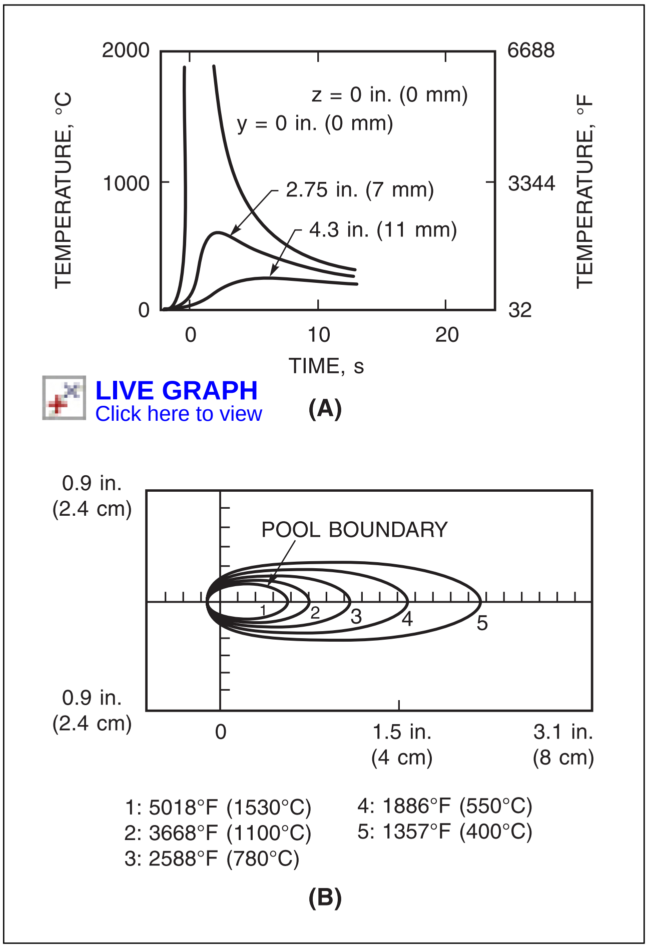
23. Rosenthal, D., 1941, Mathematical Theory of Heat Distribution during Welding and Cutting, *Welding Journal* 20: 220-s–234-s.

24. See Reference 23.
25. See Reference 3.



Source: Adapted from Kou, S., 1987, *Welding Metallurgy*, New York: John Wiley and Sons.

Figure 3.8—Calculated Results from Rosenthal's Three-Dimensional Heat Flow (See Equation [3.10]) for 1018 Steel Welded at Approximately 6 Inches per Minute (2.54 mm/s): (A) Thermal Cycles and (B) Isotherms



Source: Adapted from Kou, S., 1987, Welding Metallurgy, New York: John Wiley and Sons.

Figure 3.9—Calculated Results from Rosenthal's Three-Dimensional Heat Flow Equation (See Equation [3.10]) for 1018 Steel Welded at 14.6 in./min (6.2 mm/s) and 5 kW: (A) Thermal Cycles and (B) Isotherms

Several simplified, practical working equations are presented in the following sections. These can be used for the rough estimation of important quantities such as the cooling rate, peak temperature, width of the heat-affected zone, and solidification rate.

Cooling Rate

Thermal energy applied to the weld zone is distributed by conduction in the weldment. The resulting weld thermal cycle exhibits a temperature rise and a combination of heat loss to the environment and heat transfer to the base metal and the welding fixtures. The cooling rate experienced in the weldment is a function of the rate of energy dissipation.

The final metallurgical structure of the weld zone is determined primarily by the cooling rate from the maximum, or peak, temperature achieved during the weld cycle. Cooling rates are particularly important for heat-treatable steels. The critical cooling rate for the formation of martensite in these steels is often commensurate with that likely to be encountered in welding.[26]

26. Weldment microstructures are discussed in Chapter 4, "Welding Metallurgy."

Cooling rates vary with temperature. However, for purposes of comparison, cooling rate calculations should be made at a given temperature, T_c. In this chapter, cooling rate calculations will be made at 1020°F (550°C). The major practical use of cooling rate equations is in the calculation of preheat requirements. For instance, consider a single-weld pass in making a butt joint between two plates of equal thickness. If the plates are relatively thick, i.e., requiring more than six passes to complete the joint, the weldment cooling rate attained at the weld centerline can be approximated by means of the following expression:[27]

$$R_c = -\frac{2\pi k(T_c - T_o)^2}{H_{\text{net}}} \tag{3.12}$$

where

R_c = Cooling rate at the weld centerline, °F/min (°C/s);
π = 3.1416;
k = Thermal conductivity of the metal, Btu/(in. min °F) (cal/[cm s °C]);
T_c = Temperature at which the cooling rate is calculated, °F (°C);
T_o = Initial plate temperature °F (°C); and
H_{net} = Net heat input per unit length, Btu/in. (cal/cm).

For the calculations made in this section, k is assumed to be 0.022 Btu/(in. °F min) (0.028 J/[mm s °C]).

However, at the temperature of interest (T_c = 1022°F [550°C]), the cooling rate near the weld fusion boundary is only a few percentage points lower than that on the centerline. Accordingly, the cooling rate equation applies to the entire weld and the immediate heat-affected zone. At temperatures near the melting point (2900°F [1593°C]), the cooling rates at the centerline and the fusion boundary may differ significantly, and Equation (3.12) is valid only at the centerline.

If the plates are relatively thin (i.e., requiring fewer than four passes), the following equation can be used to determine the weldment cooling rate:[28]

$$R_c = -2\pi k\rho C\left(\frac{h}{H_{\text{net}}}\right)^2 (T_c - T_o)^3 \tag{3.13}$$

where

R_c = Cooling rate at the weld centerline, °F/min (°C/s);
π = 3.1416;
k = Thermal conductivity of the metal, Btu/(in. min °F) (cal/[cm s °C]);
ρ = Density of the base metal, lb/in.^{3} (g/cm^3);
C = Specific heat of the base metal, Btu/(lb °F) (cal/g °C);
h = Thickness of the base metal, in. (cm);
H_{net} = Net heat input per unit length, Btu/in. (cal/cm);
T_c = Temperature at which the cooling rate is calculated, °F (°C); and
T_o = Initial plate temperature, °F (°C).

The distinction between the terms *thick* and *thin* as they are used in this context requires some explanation. The thick-plate equation is used when the heat flow is three-dimensional, downward as well as laterally from the weld. The thick-plate equation would apply, for example, to a small bead-on-plate weld pass deposited on thick material. In contrast, the thin-plate equation would apply to any weld in which the heat flow is essentially lateral. A base metal is thin when the difference in temperature between the bottom and the top surfaces is small in comparison to the melting temperature.

Cooling rates for any single-pass, full-penetration welding (or thermal cutting) application can be calculated using the thin-plate equation, which is shown in Equation (3.14). However, it is not always obvious whether the plate is thick or thin because these terms have no absolute meaning. For this reason, it is helpful to define a dimensionless quantity known as the *relative plate thickness*, which is expressed as follows:

$$\tau = h\sqrt{\frac{\rho C(T_c - T_o)}{H_{\text{net}}}} \tag{3.14}$$

where

τ = Relative plate thickness;
h = Thickness of workpiece, in. (cm);
ρ = Density of the base metal, lb/in.^{3} (g/cm^3);
C = Specific heat of the base metal, Btu/(lb °F) (cal/[g °C]);
T_c = Temperature at which the cooling rate is calculated, °F (°C);
T_o = Initial plate temperature, °F (°C); and
H_{net} = Net heat input per unit length, Btu/in. (cal/cm).

The thick-plate equation applies when τ is greater than 0.9, whereas the thin-plate equation applies when τ is less than 0.6. When τ falls between 0.6 and 0.9, the upper bound of the cooling rate is given by the thick-

27. Adams, C. M., Jr., 1958, Cooling Rates and Peak Temperatures in Fusion Welding, *Welding Journal* 37(5): 210-s–215s.
28. Jhaveri, P., W. G. Moffatt, and C. M. Adams, Jr., 1962, Effect of Plate Thickness and Radiation on Heat Flow in Welding and Cutting, *Welding Journal* 41(1): 12-s–16-s.

plate equation, while the lower bound is given by the thin-plate equation.

Relative plate thickness is illustrated in Figure 3.10. If an arbitrary division is set at τ = 0.75, with larger values regarded as thick and smaller as thin, the maximum error may not exceed 15% in a cooling rate calculation. The error in applying the equations to the calculation of preheat requirements is minor.

Preheat Temperature and Critical Cooling Rate

In the cooling rate equations, increasing the initial uniform temperature, T_o, of the base metal being welded has the effect of reducing the cooling rate. Preheat is often used for this purpose when welding hardenable steels. Each particular steel composition has a critical cooling rate. If the actual cooling rate in the weld metal exceeds this critical value, hard martensitic structures may develop in the heat-affected zone, and the risk of cracking under the influence of thermal stresses in the presence of hydrogen is enhanced. The cooling rate equation can be used to determine this critical cooling rate (under welding conditions) and to calculate preheat temperatures that prevent the formation of hard heat-affected zones.

When welding hardenable steels, the first problem involves the determination of the critical cooling rate, which is defined as the slowest cooling rate to produce a martensitic structure. The simplest and most direct way of doing this is to make a series of bead-on-plate weld passes in which all variables except the arc travel speed are held constant. For example, suppose the following:

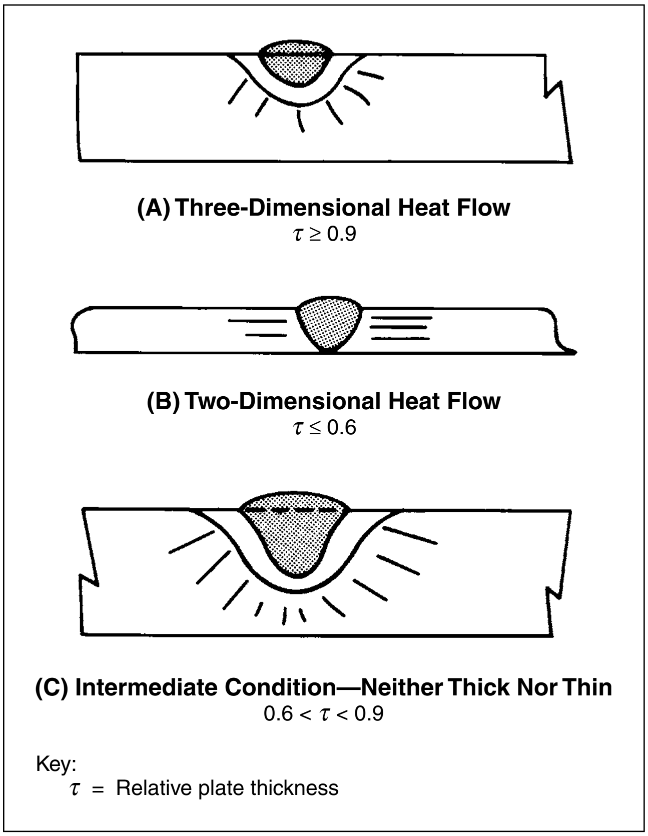
Fraction of energy absorbed, η = 0.9 (approximate value assumed for this calculation);
Thickness of the workpiece, h = 1/4 in. (6 mm);
Welding voltage, E = 25 V;
Welding current, I = 300 A;
Temperature at which the cooling rate is calculated, T_c = 1022°F (550°C); and
Initial plate temperature, T_o = 77°F (25°C).

The bead-on-plate weld passes are deposited at U = 14, 17, 19, 21, and 24 in./min (6, 7, 8, 9 and 10 mm/s). When hardness tests are subsequently performed on the weld cross sections, it can be observed that martensitic structures having a high hardness have developed in the heat-affected zones of the welds deposited at 21 and 24 in./min (9 and 10 mm/s), but not in the others.

Thus, it is determined that the critical cooling rate was encountered at some travel speed above 19 in./min (8 mm/s). More to the point, the pass deposited at 19 in./min (8 mm/s) experienced a cooling rate that is a maximum "safe" value. In this circumstance, the energy input, H_{net} (= $\eta EI/U$) is 20.3 Btu/in. (844 J/mm). The relative plate thickness can be calculated from Equation (3.15) as τ equals 0.31. Therefore, the thin-plate equation applies. Using Equation (3.14), the cooling rate can be calculated as R_c = 10.3°F/s (5.7°C/s). This result signifies that a cooling rate of approximately 11°F/s (6°C/s) is the maximum safe cooling rate for this composition of steel. Preheat can be used in actual welding operations to reduce the cooling rate to 11°F/s (6°C/s) or less.

The minimum preheat can be determined to achieve a maximum cooling rate of 11°F/s (6°C/s) for the following welding conditions:

Fraction of energy absorbed, η = 0.9;
Thickness of the workpiece, h = 3/8 in. (9 mm);
Welding voltage, E = 25 V;
Welding current, I = 250 A; and
Welding speed, U = 16.5 in./min (7 mm/s).



Source: Adapted from Adams, C. M., Jr., 1958, Cooling Rates and Peak Temperatures in Fusion Welding, *Welding Journal* 37(5): 210-s–215-s.

Figure 3.10—Effect of Weld Geometry and Relative Plate Thickness on Heat Flow Characteristics

Assuming the thin-plate equation still applies, 11°F/s (6°C/s) is substituted for R, and Equation (3.13) is solved for T_o. Thus, T_o equals 324°F (162°C). The thin-plate assumption is verified to be correct by calculating the relative plate thickness, τ, using Equation (3.14).

If it were incorrectly assumed that the thick-plate condition applied, Equation (3.12) would have been used, and a minimum required preheat of 723°F (384°C) would have been calculated. However, on substituting the appropriate values into Equation (3.14), the relative plate thickness, τ, would be 0.27. Thus, the assumption of a thick-plate condition would have been shown to be incorrect.

Therefore, a minimum preheat temperature of 324°F (162°C) would result in a maximum cooling rate of 11°F/s (6°C/s), preventing high-hardness martensite from forming in the heat-affected zone. If the same energy input were used on a plate 1 in. (25 mm) thick, the preheat temperature required to prevent a heat-affected zone with high-hardness could be calculated using the thin-plate formula, Equation (3.14), and T_o = 670°F (354°C). The relative plate thickness, τ, can then be determined to be 0.82, which is neither thick nor thin. Using Equation (3.13), it is found that the thick-plate assumption is also invalid (T_o = 733°F [389°C], and τ = 0.74). Neither of the two calculated preheat values is exactly correct. However, the difference is not of practical importance. In this case, the higher preheat temperature is the prudent choice.

Repeating the exercise for a plate that is 2 in. (50 mm) thick, but with the same energy input, the thick-plate equation, Equation (3.12), applies, and again T_o = 733°F (389°C). Using this preheat temperature to calculate the relative thickness in Equation (3.14) results in τ = 1.48. Inasmuch as τ is greater than 0.9, the assumption that Equation (3.12) applies is valid.

The selection of preheat temperatures to prevent high-hardness heat-affected zones should be guided by experience as well as by calculation whenever possible. The optimum preheat temperature is the lowest temperature that maintains the cooling rate somewhat below the critical cooling rate, thus allowing for a margin of safety.

The purpose of these calculations is to determine the minimum preheat necessary to achieve a maximum cooling rate of 11°F/s (6°C/s). Thus, if the calculation shows that the minimum preheat is –5°F (–20°C), a preheat of 76°F (25°C) would also result in a cooling rate lower than 11°F/s (6°C/s). In actual practice, a modest preheat is frequently used with hardenable steels to remove condensed moisture on work surfaces, even when cooling rate considerations do not so dictate.

Characteristic Weld Metal Cooling Curves

Cooling curves have been measured for a wide range of submerged arc welding techniques to investigate the effect of welding techniques on weld metal cooling rates.[29] Temperature-time curves can be obtained by plunging a platinum/platinum 13%-rhodium thermocouple into the melted weld pool behind the arc. A typical temperature-time curve is shown in Figure 3.11. This curve, which is typical of all arc welding studies, results from the common situation in which a high local temperature is reduced by the conduction of heat to the relatively extensive surrounding cold base metal.

As shown in Figure 3.12, a linear relationship exists between the cooling rate at 1000°F (538°C) and the average cooling rate between 1472°F and 932°F (800°C and 500°C).

The relationship between the weld cross-sectional area and the cooling rate, shown in Figure 3.13, is consistent whether the cooling rate is measured at 1000°F (538°C) or 1300°F (704°C).

Peak Temperature

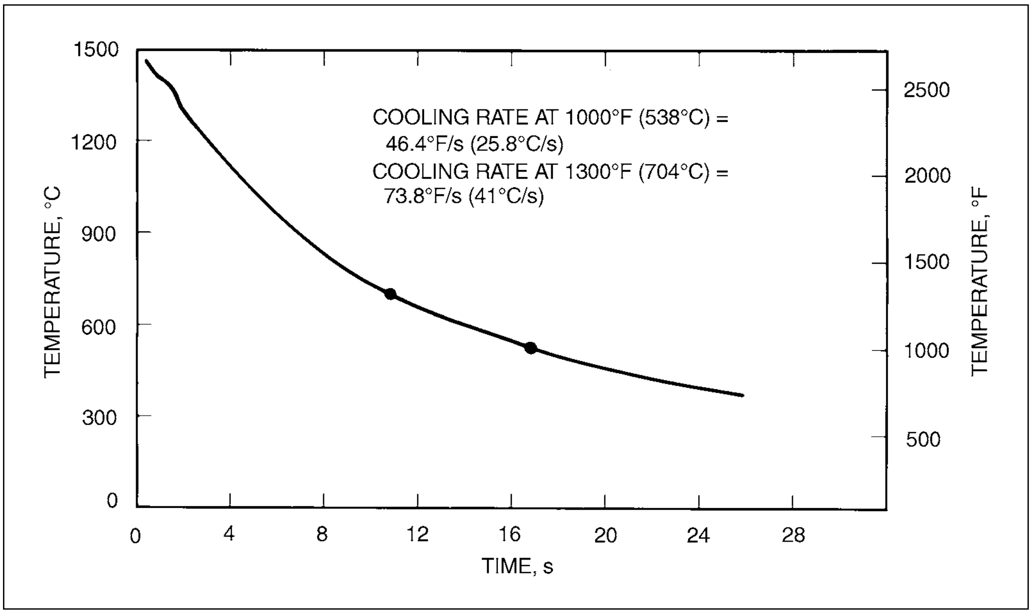
Predicting or interpreting metallurgical transformations at a point in the solid metal near a weld requires some knowledge of the maximum or peak temperature reached at a specific location. For a single-pass complete-joint-penetration butt weld in sheet or plate, for example, the distribution of the peak temperatures in the base metal adjacent to the weld is expressed by the following:[30]

$$\frac{1}{T_p - T_o} = \frac{\sqrt{2\pi e}\,\rho C h Y}{H_{\text{net}}} + \frac{1}{T_m - T_o} \tag{3.15}$$

where

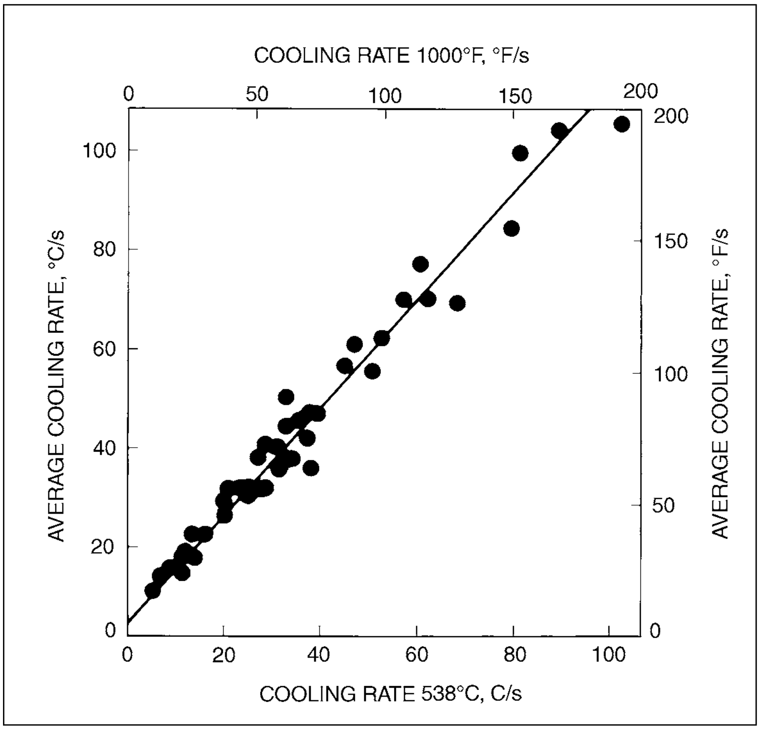
T_p = Peak or maximum temperature, °F (°C);
T_o = Initial plate temperature, °F (°C);
π = 3.1416;
e = 2.718, The base of the natural logarithms;
ρ = Density of the base metal, lb/in.^{3} (g/cm^3);
C = Specific heat, Btu/(lb °F) (cal/g °C);
h = Thickness of the workpiece, in. (cm);
Y = Distance from the weld fusion boundary, in. (cm);
H_{net} = Net heat input per unit length, Btu/in. (cal/cm); and
T_m = Melting temperature (specifically, the liquidus temperature of the metal being welded), °F (°C).

29. Dorschu, K. E., and A. Lesnewich, 1964, Development of a Filler Metal for a High-Toughness Alloy Plate Steel with a Minimum Yield Strength of 140 ksi, *Welding Journal* 43(12): 564-s–576-s.
30. See Reference 27.



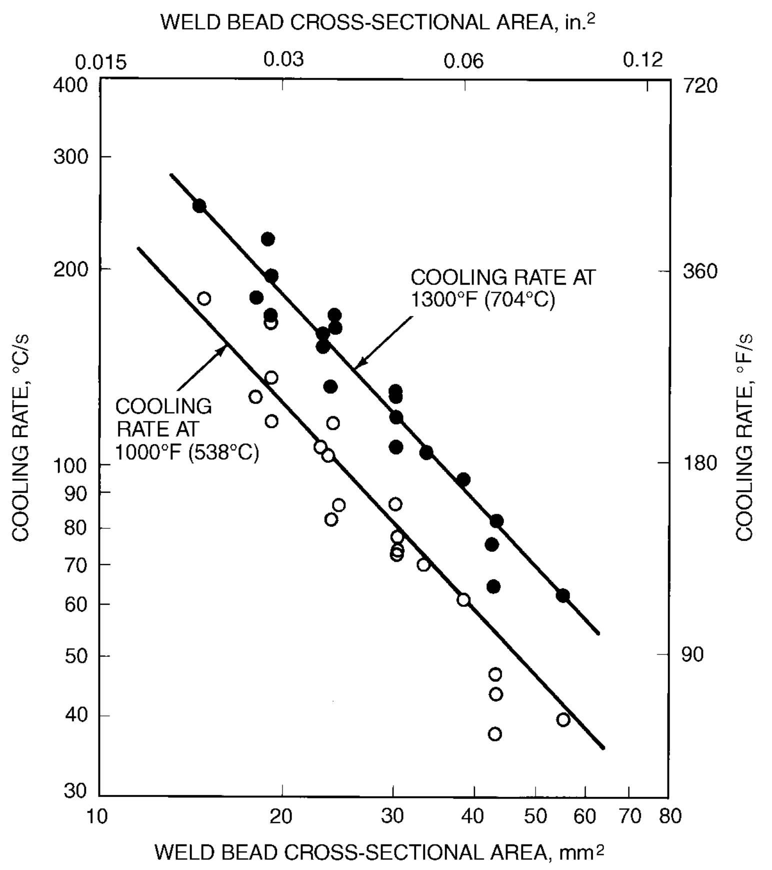
Source: Adapted from Krause, G. T., 1978, Heat Flow and Cooling Rates in Submerged Arc Welding. Master's thesis. The Ohio State University.

Figure 3.11—Temperature-Time Curve for a Bead Weld on a Plate Surface



Source: Adapted from Krause, G. T., 1978, Heat Flow and Cooling Rates in Submerged Arc Welding. Master's thesis. The Ohio State University.

Figure 3.12—Comparison of Cooling Rates as Measured by the Average Cooling Rate from 1472°F to 932°F (800°C to 500°C) and the Tangent at 1004°F (540°C)



Source: Adapted from Krause, G. T., 1978, Heat Flow and Cooling Rates in Submerged Arc Welding. Master's thesis. The Ohio State University.

Figure 3.13—Correlation between Weld Cross Section and Cooling Rate at 1000°F (538°C) and 1300°F (704°C)

The peak temperature equation does not apply at points within the weld metal, but only in the adjacent heat-affected zone. At the fusion boundary ($Y = 0$), the peak temperature, T_p, is equal to the melting temperature, T_m.

The peak temperature equation can be used for several purposes. These include (1) determining peak temperatures at specific locations in the heat-affected zone, (2) estimating the width of the heat-affected zone, and (3) demonstrating the effect of preheat on the width of the heat-affected zone.

For example, let us assume that a single complete-joint-penetration weld pass is made on steel using the following conditions:

Fraction of energy absorbed, η, = 0.9;
Specific heat of the metal, C, = 40 J/(in.^{3} °F) (0.0044 J/[mm^3 °C]);
Welding voltage, E, = 20 V;
Thickness of the workpiece, h, = 3/16 in. (5 mm);
Welding current, I, = 200 A;
Net heat input per unit length, H_{net}, = 18,300 J/in. (720 J/mm);
Melting temperature, T_m, = 2750°F (1510°C);
Initial plate temperature, T_o, = 77°F (25°C); and
Welding speed, U, = 12 in./min (5 mm/s).

The peak temperature at 1/16 in. and 1/8 in. (1.5 mm and 3.0 mm) from the fusion boundary can be calculated from Equation (3.15). Thus, at Y = 1/16 in. (1.5 mm), T_p = 2160°F (1182°C). At Y = 1/8 in. (3.0 mm), T_p = 1790°F (976°C).

Though the peak temperature equation can be very instructive and useful, it is important to recognize certain restrictions in its application. The most important of these is that the equation is derived for the so-called "thin-plate" condition, in which heat conduction takes place along paths that are parallel to the plane of the plate. The equation thus applies to any single-pass full-penetration welding or thermal cutting process, regardless of plate thickness. The equation must be applied on a per-pass basis; however, the interpass temperature (the temperature to which the weld region cools between passes) should be inserted as a value for T_o in the peak temperature equation.

Width of the Heat-Affected Zone

If the peak temperature is defined as being a temperature below which the welding heat does not affect the properties of the base metal, Equation (3.15) can be used to calculate the width of the heat-affected zone. The mechanical properties of most plain carbon and low-alloy steels are not affected if the peak temperature is below approximately 1350°F (732°C). Using 1350°F (732°C) for T_p in Equation (3.15), the width of the heat-affected zone, Y_z, is 0.23 in. (5.9 mm).

If a heat-treated steel is tempered at 806°F (430°C), any region heated above 806°F (430°C) will, in theory, be "overtempered" and exhibit modified properties. The width of the heat-affected zone, including the entire overtempered region, can be calculated by substituting 806°F (430°C) into Equation (3.15). Steels that respond to a quench-and-temper heat treatment are frequently preheated prior to welding. From Equation (3.15), it can be observed that this treatment has the side effect of widening the heat-affected zone.

One of the simplest and most important conclusions that may be drawn from the peak temperature equation is that the width of the heat-affected zone is proportional to the heat input. However, the peak temperature equation is an approximation that is reasonably accurate within the normal ranges of heat input encountered in welding operations. Within these limits, the width of the heat-affected zone increases proportionally with the net heat input.

Solidification Rate

The rate at which the weld metal solidifies can have a profound effect on its metallurgical structure, properties, and response to heat treatment. The solidification time, S_t, of the weld metal depends on the net energy input, as indicated below:

$$S_t = \frac{LH_{\text{net}}}{2\pi k\rho C(T_m - T_o)^2} \tag{3.16}$$

where

S_t = Solidification time, which is taken as the time lapse from beginning to the end of solidification at a fixed point in the weld metal, min (s);
L = Heat of fusion, which for steels is approximately 31 Btu/in.^{3} (2 J/mm^3);
H_{net} = Net heat input per unit length, Btu/in. (cal/cm);
π = 3.1416;
k = Thermal conductivity of the melt, Btu/(min in. °F) (cal/[cm s °C]);
ρ = Density of the base metal, lb/in.^{3} (g/cm^3);
C = Specific heat of the base metal, Btu/(lb °F) (cal/[g °C]);
T_m = Melting temperature, °F (°C); and
T_o = Initial plate temperature, °F (°C).

Solidification time, S_t, is a function of the energy input and the initial temperature of the metal. If, for example, a weld pass of 20,300 J/in. (800 J/mm) net energy input is deposited on a steel plate with an initial temperature of 77°F (25°C), then from Equation (3.16), S_t is determined to be 0.94 seconds.

In comparison to solidification in the casting processes, weld metal solidification is extremely rapid. The final microstructure of a casting and a weld are both dendritic, but the differences in structure are much greater than the similarities. The mass of liquid weld metal is extremely small relative to the mass of solid metal in virtually all weldments, and the thermal contact between the liquid and solid metal is excellent. As a result of this combination of factors, the heat is rapidly removed from the weld pool. In contrast, the mass of liquid metal in most commercial castings is large in comparison to the surrounding mold, and the thermal contact with the mold is not as efficient as in the case of weld metals. These factors lead to long solidification times for castings as compared to those for weld metal.

CONVECTIVE HEAT TRANSFER IN THE WELD POOL

Convective heat transfer is often very important in determining the size and shape of the weld pool, the weld macro- and microstructures, and the weldability of the material. On the whole, convection is driven by the surface tension gradient, buoyancy, jet impingement or friction, and when electric current is used, electromagnetic forces. Calculations of convective heat transfer in the weld pool are routinely performed through the numerical solution of the equations of conservation of mass, heat, and momentum.[31]

Because welding processes are highly complex, the extent of simplification that can be tolerated for a particular application must be determined. Three-dimensional versus two-dimensional simulations, transient versus steady-state, a flat weld pool surface versus a free deformable surface, laminar flow in the weld pool versus turbulent flow are examples of the available choices. The consequences of such choices vary, depending on the goals of the simulation effort. In view of these complexities, attempts to understand welding processes through simulation must involve concomitant, well-designed experimental work to validate the convective heat transfer calculations.

DRIVING FORCES

Several driving forces for fluid flow are present in the weld pool. They include the Maragoni, buoyancy, electromagnetic, and arc-shear forces.

Marangoni Force

The spatial gradient of surface tension is a stress known as *Marangoni stress*. This stress may arise as a result of variations of both temperature and composition of the weld metal. Frequently, convection in the weld pool results mainly from Marangoni stress, which is determined by the temperature gradient at the surface of the weld pool. The spatial gradient of surface tension is the product of the spatial gradient of temperature and the slope of the surface tension versus temperature plot. Marangoni stress can be expressed as follows:

$$\tau = \frac{d\gamma}{dT}\frac{dT}{dy} \tag{3.17}$$

where

τ = Shear stress due to the temperature gradient, lb/(in. min^2) (g/[cm s^2]);
$d\gamma/dT$ = Temperature coefficient of surface tension, lb/(min^2 °F) (g/[s^2 °C]); and
dT/dy = Spatial gradient of temperature, °F/in. (°C/cm)

If a boundary layer develops, the shear stress can be expressed as:[32]

$$\tau = \frac{0.332\rho^{1/2}\mu^{1/2}u^{1/2}}{y^{1/2}} \tag{3.18}$$

where

τ = Shear stress, lb/(in. min^2) (g/[cm s^2]);
ρ = Density of the base metal, lb/in.^{3} (g/cm^3);
μ = Viscosity, lb/(in. min) (g/[cm s]);
u = Local velocity, in./min (cm/s); and
y = Distance along the surface from the axis of the heat source, in. (cm).

An order of magnitude of the maximum velocity, u_m, can be calculated by combining Equations (3.17) and (3.18) and assuming that the maximum velocity occurs at a location approximately halfway between the heat source axis and the edge of the weld pool, i.e., at $y = W/4$, where W is the width of the weld pool:

$$u_m^{3/2} \approx \frac{d\gamma}{dT}\frac{dT}{dy}\frac{w^{1/2}}{0.664\rho^{1/2}\mu^{1/2}} \tag{3.19}$$

where

u_m = Maximum velocity, in./min (cm/s);
$d\gamma/dT$ = Temperature coefficient of surface tension, lb/(min^2 °F) (g/[s^2 °C]);
dT/dy = Spatial gradient of temperature, °F/in. (°C/cm);
w = Width of the weld pool, in. (cm);
ρ = Density, lb/in.^{3} (g/cm^3); and
μ = Viscosity, lb/(in. min) (g/[cm s]).

For a typical weld pool with a width of 0.197 in. (0.5 cm), a metal density of 0.26 lb/in.^{3} (7.2 g/cm^3), a viscosity of 0.02 lb/(in. min) (0.06 g/cm s), a temperature coefficient of surface tension *($d\gamma/dT$)* of 2.21 lb/min^2 °F (0.5 dynes/cm °C), and a spatial gradient temperature of 2743°F/in. (600°C/cm), the maximum velocity is approximately 1465 in./min (62 cm/s). Considering that this weld pool is only 0.197 in. (0.5 cm) wide, this velocity is rather high. Computed values of the order of 2362 in./min (100 cm/s) have been reported in systems dominated by Marangoni convection.

When the velocities are low, shear stress, τ, cannot be accurately estimated by Equation (3.19), which is based on the boundary layer theory. For such a situation, a rough estimate of the shear stress can be obtained from geometric consideration as $2u_m/d$, where d denotes the depth of the weld pool. The expression for the approximate value of the maximum velocity can be obtained by combining the expression for shear stress (Equation

31. See Reference 20.
32. Geankoplis, C. J, 1983, *Transport Processes and Unit Operations,* Boston: Allyn and Bacon.

[3.18]) with the expression for Marangoni stress (Equation [3.17]), as follows:

$$u_m \approx \frac{d}{2\mu}\frac{d\gamma}{dT}\frac{dT}{dy} \tag{3.20}$$

where

u_m = Maximum velocity, in./min (cm/s);
d = Depth of the weld pool, in. (cm);
$d\gamma/dT$ = Temperature coefficient of surface tension, lb/(min^2 °F) (g/[s^2 °C]);
dT/dy = Spatial gradient of temperature, °F/in. (°C/cm); and
μ = Viscosity, lb/(in. min) (g/[cm s]).

The velocities calculated from Equations (3.19) and (3.20) provide a rough idea of the maximum velocity of liquid metal in the weld pool. Detailed solutions of the equations of conservation of mass, momentum, and heat are necessary for the calculation of temperature and velocity fields in the weld pool.

Buoyancy and Electromagnetic Forces

When the surface tension gradient is not the main driving force, the maximum velocities can be much lower. For example, when the flow occurs owing to natural convection, the maximum velocity can be approximated by the following relation:[33]

$$u_m \approx \sqrt{g\beta\Delta T d} \tag{3.21}$$

where

u_m = Maximum velocity, in./min (cm/s);
g = Acceleration due to gravity, in./min^2 (cm/s^2);
β = Coefficient of volume expansion, 1/°F (1/°C);
ΔT = Temperature difference, °F (°C); and
d = Depth of the weld pool, in. (cm)

For the values of ΔT = 1080°F (ΔT = 600°C), $g = 1.38 \times 10^6$ in./min^2 (981 cm/s^2), $\beta = 1.94 \times 10^{-5}$/°F ($3.5 \times 10^{-5}$/°C), and d = 0.197 in. (0.5 cm), the value of u_m is 75.6 in./min (3.2 cm/s).

In the case of electromagnetically driven flow in the weld pool, the velocity values reported in the literature are typically in the range of 3.9 ft/min to 39.4 ft/min (2 cm/s to 20 cm/s).[34] The magnitude of the velocities for both buoyancy and electromagnetically driven flows in the weld pool are commonly much smaller than those obtained for surface-tension-driven flows.

The electromagnetic force in the weld pool increases as the arc becomes more constricted and produces a change in the motion of the weld pool. In gas tungsten arc welding, the arc is more constricted as the vertex angle of the conical tip of the thoriated tungsten electrode increases.[35] This favors convective heat transfer from the arc to the bottom of the weld pool,[36] thus producing deeper joint penetration, as shown in Figure 3.14. In this figure, the values in the column on the left specify the diameters of the conical truncation, 0.005 in. (0.125 mm) and 0.020 in. (0.500 mm).

Inaccuracies in the computed velocities result from several sources. First, the presence of impurities on the surface is known to lower the impact of surface-tension-driven flow. Second, for convective heat flow calculations, values of viscosity and thermal conductivity higher than the respective molecular values are necessary to account for the higher rates of heat transport and momentum in agitated weld pools. These enhanced transport parameters are traditionally determined from turbulence models. However, the widely used turbulence models contain several empirical constants determined from parabolic flows in large systems. These models have not been adequately tested in the simulation of welding. Finally, inaccuracies also result from the lack of appropriate thermophysical data. For example, only limited data are available regarding the effect of plasma in influencing the temperature dependence of surface tension.[37] Such data are important for the calculation of Marangoni convection.

These uncertainties become important when convection is the principal mechanism of heat transfer. Trends in the computed velocities and temperatures as a function of a welding variable such as heat source intensity are more dependable than the exact computed velocity field values under a given set of welding conditions. The detailed experimental determination of flow velocities and temperatures in the weld pool remains a major challenge in the field.[38] In the absence of adequate

33. Szekely, J., 1986, The Mathematical Modeling of Arc Welding Operations, in *Advances in Welding Science and Technology*, ed. S. A. David, Materials Park, Ohio: ASM International, pp. 3–14.

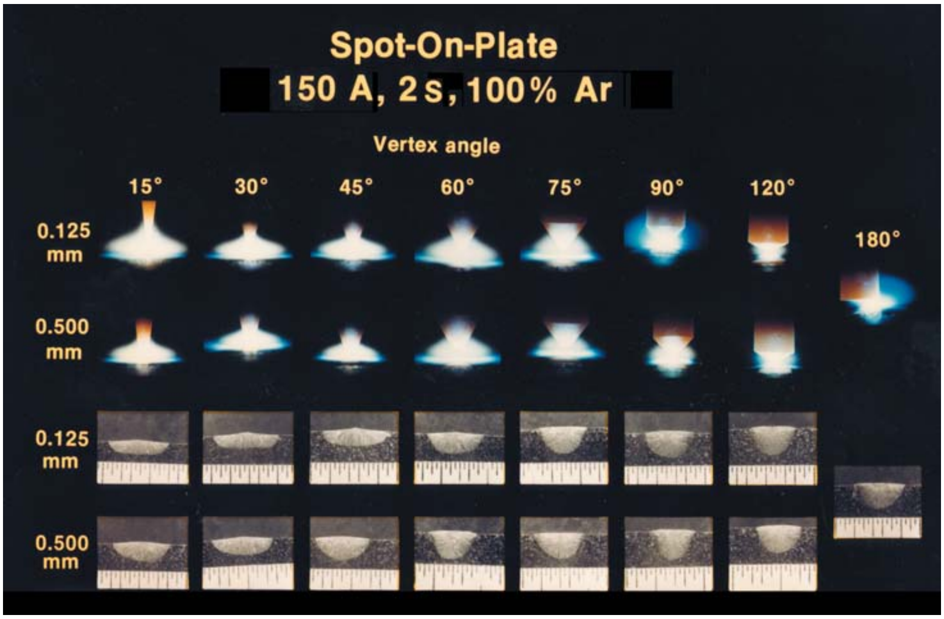
34. Wang, Y. H., and S. Kou, 1986, Driving Forces for Convection in Weld Pools, in *Advances in Welding Science and Technology*, ed. S. A. David, Materials Park, Ohio: American Society for Metals International.

35. Key, J. F., 1980, Anode/Cathode Geometry and Shielding Gas Interrelationships in GTAW, *Welding Journal* 59: 364-s–370-s.

36. Kou, S., and D. K. Sun, 1985, Fluid Flow and Weld Penetration in Stationary Arc Welds, *Metallurgical Transactions A* 16A: 203–213.

37. Sahoo, P., T. DebRoy, and M. J. McNallan, 1988, Surface Tension of Binary Metal-Surface Active Solute Systems under Conditions Relevant to Welding Metallurgy, *Metallurgical Transactions B* 19B: 483–491.

38. Mazumder, J., 1993, Validation Strategies for Heat-Affected Zone and Fluid Flow Calculations, in *Welding, Brazing, and Soldering*, Vol. 6 of *ASM Handbook*, eds. J. R. Davis, K. Ferjutz, and N. D. Wheaton, Materials Park, Ohio: American Society for Metals International.



Note: 0.125 mm = 0.005 in. and 0.500 mm = 0.020 in.

Source: Key, J. F., 1980, Anode/Cathode Geometry and Shielding Gas Interrelationships in GTAW. *Welding Journal* 59(12): 364-s–370-s.

Figure 3.14—Arc Shape and Weld Bead Geometry as a Function of Electrode Tip Angle in a Pure Argon Shield

experimental work, contemporary literature relies heavily on numerical calculations of convective heat flow in the weld pool.

RELATIVE IMPORTANCE OF CONDUCTION AND CONVECTION

The relative importance of conduction and convection in the overall transport of heat in the weld pool can be assessed from the value of the Peclet number, *Pe*, which is given by:

$$Pe = \frac{u \rho c_p L}{k} \tag{3.22}$$

where

Pe = Peclet number;
u = Velocity, in/min (cm/s);
ρ = Density, lb/in.^{3} (g/cm^3);
c_p = Specific heat at constant pressure, Btu/(lb °F) (cal/[g °C]);
L = Characteristic length, in. (cm); and
k = Thermal conductivity of the melt, Btu/(in. °F min) (cal/([cm °C s]).

For a typical case in which u = 232.2 in./min (10 cm/s), ρ = 0.26 lb/in.^{3} (7.2 g/cm^3), c_p = 0.2 Btu/(lb °F) (0.2 cal/[g °C]), L = 0.197 in. (0.5 cm), and k = 0.0336 Btu/(in. min °F) (0.1 cal/[cm s °C]), the Pe is 72. When the Peclet number is much larger than 1.0, heat transport occurs primarily by convection, and heat conduction in the weld pool is not important. However, for metals with high thermal conductivities, at low velocities, and for small-sized pools, the value of Pe can be low (e.g., $Pe \ll 1$). In this case, accurate calculations of heat transfer can be done using relatively simple heat conduction calculations.

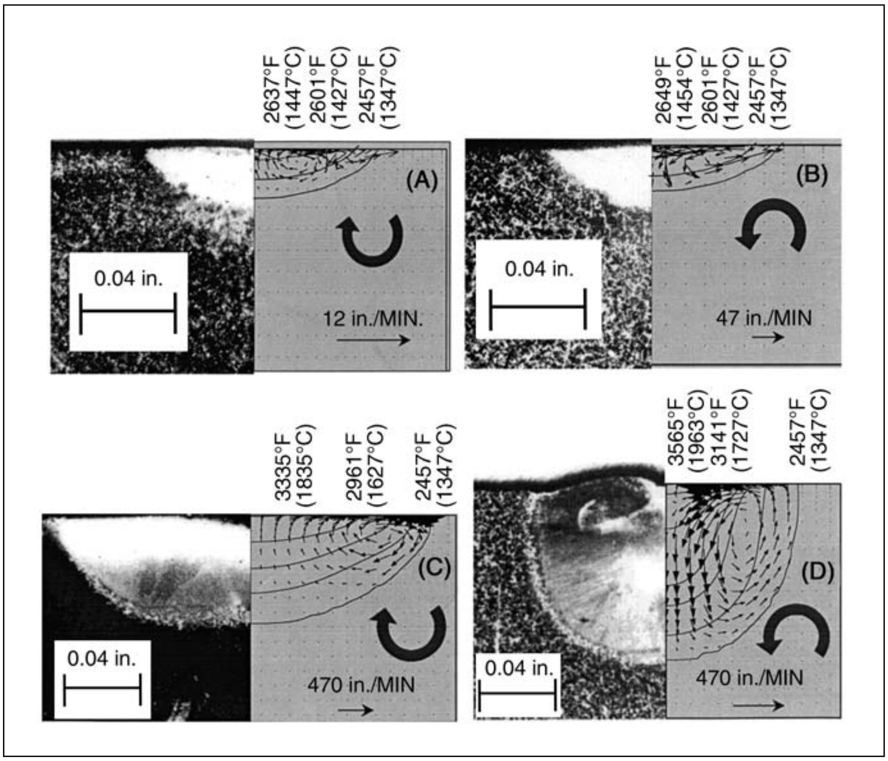
It should also be noted that the conduction of heat in the solid region is very important for the dissipation of heat away from the weld pool. Therefore, the thermal conductivity of the solid and the specimen dimensions are very important in determining the size of the molten pool.

VARIABLE PENETRATION

Numerical calculations of heat transfer and fluid flow have provided detailed insight that could not have been achieved otherwise. One example is the variable depth of penetration of welds during the welding of different joints made of the same grade of steel under identical welding conditions. The beneficial effects of surface-active elements, such as sulfur and oxygen, in improving weld penetration are well known.[39] What has been puzzling is that in many cases the presence of sulfur has not actually resulted in the expected high depth of penetration.

For example, cross sections of steel welds containing 20 and 150 parts per million (ppm) of sulfur that have been laser welded under different powers are shown in Figure 3.15. At a laser power of 1900 W, the pool geometries in the two steels are similar. However, when the samples are welded at a laser power of 5200 W, the weld containing 150 ppm sulfur has a much greater depth of penetration than that containing 20 ppm sulfur. Thus, the concentration of sulfur may or may not

39. Heiple, C. R., and J. R. Roper, 1982, Mechanism for Minor Element Effect on GTA Fusion Zone Geometry, *Welding Journal* 61(4): 97-s–102-s; Heiple, C. R., J. R. Roper, R. T. Stagner, and J. J. Alden, 1982, Surface Active Element Effects on the Shape of GTA, Laser, and Electron Beam Welds, *Welding Journal* 62(3): 72-s–77-s.



Source: Adapted from Pitscheneder, W., T. DebRoy, K. Mundra, and R. Ebner, 1996, Role of Sulfur and Processing Variables on the Temporal Evolution of Weld Pool Geometry during Multikilowatt Laser Welding of Steels, *Welding Journal* 75: 71-s–80-s.

Figure 3.15—Comparison of the Computed and Experimental Weld Pool Geometries at a Laser Power of 1900 W for Steels Containing (A) 20 ppm and (B) 150 ppm Sulfur and at a Laser Power of 5200 W for Steels Containing (C) 20 ppm and (D) 150 ppm Sulfur

have a significant effect on weld geometry under the given conditions of the laser power and other welding variables.

Why did the higher sulfur concentration fail to improve penetration at 1900 W? In general, for counterintuitive results, a possible lack of reproducibility of the data cannot be ruled out. However, in this investigation, over 80 experiments were carefully conducted, and the results were reproducible. These results lead to an important question: How can weld penetration be controlled? The answer to this question requires a discussion of numerically computed results.

First, the relative magnitude of heat transfer by convection and conduction within the weld pool (Pe) is calculated from Equation (3.22). In the calculation of Pe, the value of the local velocity, u, is required. Figure 3.15 shows the computed velocity, temperature fields, and weld geometries.

In all cases, the computed weld geometries are in good agreement with the corresponding experimental data. At a laser power of 1900 W, the peak temperatures reached on the weld pool surface are both about 2640°F (1449°C). The relatively low temperature gradients on the weld pool surface lead to low surface velocities. The maximum values of the Peclet number for the steels with 20 and 150 ppm sulfur are 0.18 and 0.91, respectively. These low Pe values (<1) indicate that heat transfer by conduction is more important than that by convection. As a result, the direction of fluid flow is not important in determining the melting of the base metal and the weld pool shape at this laser power. Consequently, no significant difference exists between the weld pool geometries for steels containing 20 ppm and 150 ppm sulfur.

In contrast, at a laser power of 5200 W, the computed Peclet numbers are large (>200), making convective heat transport the primary mechanism for heat transfer.[40] Thus, the fluid flow field and the direction of convective heat transport have a pronounced effect on weld pool geometry. The direction of the fluid flow within the weld pool depends on the spatial gradient of interfacial tension, which is the product of the spatial gradient of temperature, dT/dy and the temperature gradient of surface tension, $d\gamma/dy$. For a sulfur content of 20 ppm, the temperature gradient of surface tension is negative above 2600°F (1427°C).[41] The negative values of $d\gamma/dT$ over the weld pool surface result in radially outward flow over the entire weld pool surface as well as a shallow weld pool.

When the sulfur content is 150 ppm, the convection pattern is radially inward, and the convective heat transport in the downward direction near the heat source results in deep pools, as can be observed from Figure 3.15(D). Since $d\gamma/dT$ is negative at temperatures higher than 3100°F (1704°C) for the steel containing 150 ppm sulfur, it generates a radially outward secondary flow in a small region near the middle of the pool. However, this secondary flow is mild, and a deep weld pool is obtained at 150 ppm sulfur because of the dominant radially inward flow and high Peclet number.

Only when convection is the dominant mechanism of heat transfer can surface-active elements play an important role in enhancing weld penetration. The use of a well-tested mathematical model for convective heat transport and careful assessment of the concentrations of surface active elements such as oxygen and sulfur are useful for the accurate prediction of weld pool geometry.

SIMPLE FEATURES OF SOLIDIFICATION STRUCTURE

The cooling rate at a given solidification front location is the product of the temperature gradient and the solidification growth rate. For several alloys, secondary dendrite arm spacings in the newly formed solid have been experimentally correlated with the cooling rates. Therefore, using numerically computed cooling rates and the available experimental correlation, secondary dendrite arm spacing in these alloys can be estimated. The experimental correlations between secondary dendrite arm spacing and the cooling rate obtained by Abdulgadar[42] and Bower, Strachan, and Flemings[43] are shown in Figure 3.16.

Paul and DebRoy have calculated cooling rates at the edge of the weld pool from the numerical calculations of convective heat transfer.[44] These cooling rates have been used to determine secondary dendrite arm spacing. For example, secondary dendrite arm spacings of 0.9 μm and 0.4 μm were obtained for computed cooling rates for 11.8 in./min (5 mm/s) 73.2 in./min (31 mm/s) welding speeds, respectively. As shown in Figure 3.16, these values were in good agreement with the experi-

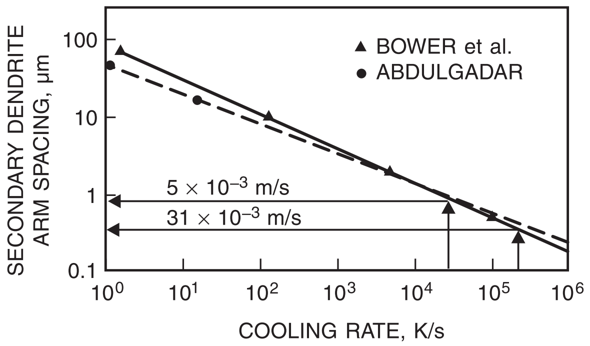
40. Pitscheneder, W., T. DebRoy, K. Mundra, and R. Ebner, 1996, Role of Sulfur and Processing Variables on the Temporal Evolution of Weld Pool Geometry during Multikilowatt Laser Welding of Steels, *Welding Journal* 75: 71-s–80-s.

41. Sahoo, P., T. DebRoy, and M. J. McNallan, 1988, Surface Tension of Binary Metal-Surface Active Solute Systems Under Conditions Relevant to Welding Metallurgy, *Metallurgical Transactions B* 19B: 483–491; McNallan, M. J., and T. DebRoy, 1991. Effect of Temperature and Composition on Surface Tension in Fe-Ni-Cr Alloys Containing Sulfur, *Metallurgical Transactions B* 22B: 557–560.

42. Abdulgadar, S. A., 1988, Laser Welding of 200-Series Stainless Steels: Solidification Behavior and Microstructure Characteristics, Ph.D. diss., The Pennsylvania State University.

43. Bower, W. E., R. Strachan, and M. C. Flemings, 1970, Effect of Cooling Behavior on Structure of Ferrous Alloys, *American Foundrymen's Society (AFS) Cast Metals Research Journal* (December): 176–180.

44. Paul, A. J., and T. DebRoy, 1988, Free Surface Flow and Heat Transfer in Conduction Mode Laser Welding, *Metallurgical Transactions B* 19B: 851–858.



Note:
5×10^{-3} m/s = 11.8 in./min
31×10^{-3} m/s = 73.2 in./min
1 K/s = 108°F/min
1 μm = 3.94×10^{-5} in.

Source: Adapted from Paul, A. J., and T. DebRoy, 1988, Free Surface Flow and Heat Transfer in Conduction Mode Laser Welding, *Metallurgical Transactions B* 19B: 851–858. Data from Bower, W. E., R. Strachan, and M. C. Flemings, 1970, Effect of Cooling Behavior on Structure of Ferrous Alloys, American Foundrymen's Society (AFS) Cast Metals Research Journal (December): 176–180; and Abdulgadar, S. A., 1988, Laser Welding of 200-Series Stainless Steels: Solidification Behavior and Microstructure Characteristics, Ph.D. diss., The Pennsylvania State University.

Figure 3.16—Plot of Secondary Dendrite Arm Spacing as a Function of Cooling Rate for the Conduction-Mode Laser Welding of AISI-201 Stainless Steel

mental results of Paul and DebRoy.[45] The agreement between the predicted secondary dendrite arm spacing and the values obtained from independent data demonstrates that the calculated values of cooling rates are fairly accurate.

In another investigation of the effect of pulsed laser welding on the thermal response of 310 and 316 austenitic stainless steels,[46] the cooling rates were theoretically calculated from fundamental principles of transport phenomena. The secondary dendrite arm spacings were determined from the microstructures. The results indicated excellent agreement between the measured and the expected secondary dendrite arm spacings based on the cooling rates. The investigations with both continuous[47] and pulsed[48] heat sources indicate that simple features of the solidification structure can be determined from the available numerical models of weld pool transport phenomena.

CONCLUSION

Traditionally, heat flow calculations have focused on the analytical solution of the heat conduction equation to obtain information regarding thermal cycles, cooling rates, the size of the heat-affected zone, and other important parameters. In recent years, with the availability of high-speed computers, more rigorous heat transfer calculations have been undertaken. These calculations have considered heat transfer by conduction and convection as well as variable thermophysical properties and phase changes. Quantitative calculations of weld geometry, composition, and structure[49] have been possible based on rigorous numerical heat flow calculations. These calculations have provided significant insight into the welding processes and welded materials that could not have been obtained otherwise. The examples provided in this chapter demonstrate that the quality of the calculated results can be improved by using large numerical models of heat flow that contain a detailed description of important physical processes.

However, comprehensive numerical calculations of heat flow in fusion welding are not widely used by practicing welding engineers. First, these calculations are generally unsuitable for real-time welding applications since they require extensive computer time. Second, the calculations are highly complex and costly, and they require extensive user training. Finally, the numerical models available in the literature have not been adequately standardized. These problems must be overcome to gain wider acceptability of the numerical calculations of heat flow in fusion welding.

In addition to being potentially more useful to practicing engineers, comprehensive heat flow models constitute a powerful tool for research today. Comprehensive heat flow calculations serve as a basis for the quantitative understanding of weldment geometry, composition, and structure. Thus, these calculations represent a contribution to an expanding quantitative

45. See Reference 44.
46. Zacharia, T., S. A. David, J. M. Vitek, and T. DebRoy, 1989, Heat Transfer during Nd-YAG Pulsed Laser Welding and Its Effect on Solidification Structure of Austenitic Stainless Steels, *Metallurgical Transactions A* 20A: 957–967.
47. See Reference 44.
48. See Reference 46.

49. Pitscheneder, W., T. DebRoy, K. Mundra, and R. Ebner, 1996, Role of Sulfur and Processing Variables on the Temporal Evolution of Weld Pool Geometry during Multikilowatt Laser Welding of Steels, *Welding Journal* 75: 71-s–80-s; Yang, Z., and T. DebRoy, 1997, Weld Metal Microstructure Prediction from Fundamentals of Transport Phenomena and Phase Transformation Theory, *Science and Technology of Welding and Joining* 2(2): 53–58; DebRoy, T., 1997, Mathematical Modeling of Geometry, Composition, and Structure of Welds, in *Proceedings of the Julian Szekely Symposium on Materials Processing*, eds. H. Y. Sohn, J. W. Evans, and D. Apelian, Warrendale, Pennsylvania: The Minerals, Metals, and Materials Society.

knowledge base in the field of welding. Significant expansion of this knowledge base is necessary, if not essential, for the evolution of welding into a mainstream quantitative engineering science.

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CHAPTER 4

WELDING METALLURGY

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Photograph courtesy of Edison Welding Institute

CHAPTER 4

WELDING METALLURGY

INTRODUCTION

The various metallurgical phenomena involved in welding—melting, freezing, diffusion, precipitation, solid-state transformations, thermal strains, and shrinkage stresses—can cause many practical concerns. These problems can be addressed by applying the appropriate metallurgical principles to the welding process. Welding metallurgy differs from conventional metallurgy in certain important respects. However, a broad knowledge of physical metallurgy is necessary in order to understand welding metallurgy. For this reason, the topic of physical metallurgy is addressed first in this chapter. This discussion is followed by an examination of the specifics of welding metallurgy.

PHYSICAL METALLURGY

The field of physical metallurgy relates not only to the study of the structure of metals and their properties but also to the science and technology of the extraction of metals from their ores, their refining, and preparation for use (alloying, rolling, heat treating, and so forth). Considering that the field is so broad, the survey of physical metallurgy that follows is by no means exhaustive. Those who wish to increase their knowledge of the discipline or who are interested in specific subject matter or specialty materials are therefore directed to the resources cited in the Bibliography and Supplementary Reading List at the conclusion of this chapter and to other volumes of the *Welding Handbook*.

STRUCTURE OF METALS

Solid metals have a crystalline structure. The atoms composing each crystal are arranged in a specific geometric pattern. This orderly arrangement of the atoms, termed a *lattice*, is responsible for many properties of metals. The most common crystalline structures in metals are the face-centered cubic, body-centered cubic, and hexagonal close-packed lattices. The most common lattice structures found in metals are listed in Table 4.1. Their atomic arrangements are illustrated in Figure 4.1.

In the liquid state, the atoms composing metals have no orderly arrangement. The atoms are amorphous like water or glass. As the liquid metal approaches the solidification temperature, solid particles known as *nuclei* begin to form at preferred sites, as shown in Figure 4.2(A).

As shown in Figure 4.2(B), solidification proceeds as the individual nuclei grow into larger, solid particles called *grains*. As the amount of solid metal increases,

Table 4.1
Crystalline Structures of Common Metals

Face-Centered Cubic [see Figure 4.1(A)]	
Aluminum	Iron†
Cobalt*	Lead
Copper	Nickel
Gold	Silver
Body-Centered Cubic [see Figure 4.1(B)]	
Chromium	Titanium‡
Iron†	Tungsten
Molybdenum	Vanadium
Niobium	Zirconium‡
Hexagonal Close-Packed [see Figure 4.1(C)]	
Cobalt*	Titanium‡
Magnesium	Zinc
Tin	Zirconium‡

* Cobalt possesses a face-centered cubic structure at high temperature but transforms to a hexagonal close-packed structure at lower temperatures.
† Iron possesses body-centered cubic structure near the melting temperature and again at low temperatures, but at intermediate temperatures, its structure is face-centered cubic.
‡ Titanium and zirconium possess a body-centered cubic structure at high temperature, but a hexagonal close-packed structure at lower temperatures.

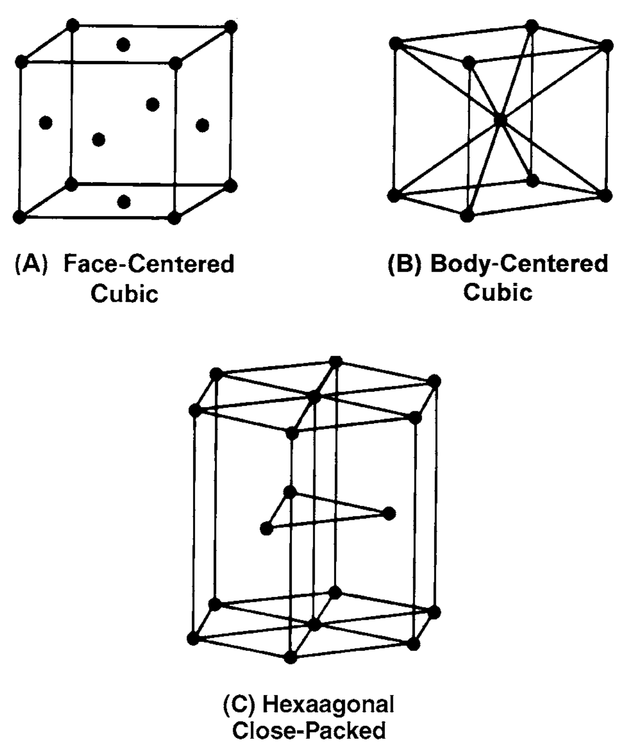


Figure 4.1—Three Most Common Crystalline Structures in Metal

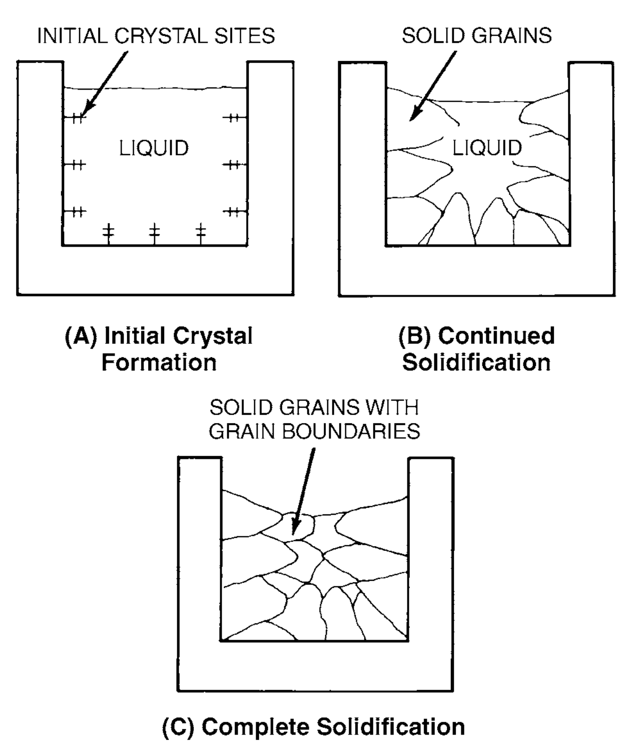


Figure 4.2—Solidification of a Metal

the amount of liquid metal decreases proportionately until the grains grow so large that there is no liquid between them. Solidification is complete at this point. As illustrated in Figure 4.2(C), the grains meet at irregular boundaries, which are referred to as *grain boundaries*.

At any given temperature, each grain in a pure metal has the same crystalline structure and the same atomic spacing as all other grains. However, each grain grows independently, and the lattice orientation of the grain differs from one grain to another. The periodic and orderly arrangement of the atoms is disrupted where the grains meet. These grain boundaries form a continuous network throughout the metal. The mechanical properties of metals are often dependent upon the size of the grains, the orientation of individual grains, and the composition of the metal.

ALLOYS

The metals commonly used in engineering contain intentionally added or residual metallic and nonmetallic elements, which are dissolved in the matrix. Those which are intentionally added, termed *alloying elements*, affect the properties of the base metal. The atomic arrangement (crystalline structure), the chemical composition, and the thermal and mechanical histories all have an influence on the properties of alloys. The alloying elements, known as *solutes*, are located in the parent metal matrix in one of two ways.

Substitutional alloying occurs when the solute atoms occupy lattice sites by replacing some atoms in the parent metal, termed the *solvent*. This process is illustrated in Figure 4.3(A). The type of alloy formed is referred to as a *substitutional solid-solution alloy*. Examples of substitutional solid solutions are gold dissolved in silver and copper dissolved in nickel.

Interstitial alloying occurs when the alloying atoms are small enough in relation to the parent-metal atoms that they can locate (or dissolve) in the spaces between the parent-metal atoms without occupying lattice sites. This type of alloy, which is illustrated in Figure 4.3(B), is termed an *interstitial solid-solution alloy*. Small amounts of carbon, nitrogen, boron, oxygen, and hydrogen can alloy interstitially in iron and other metals.

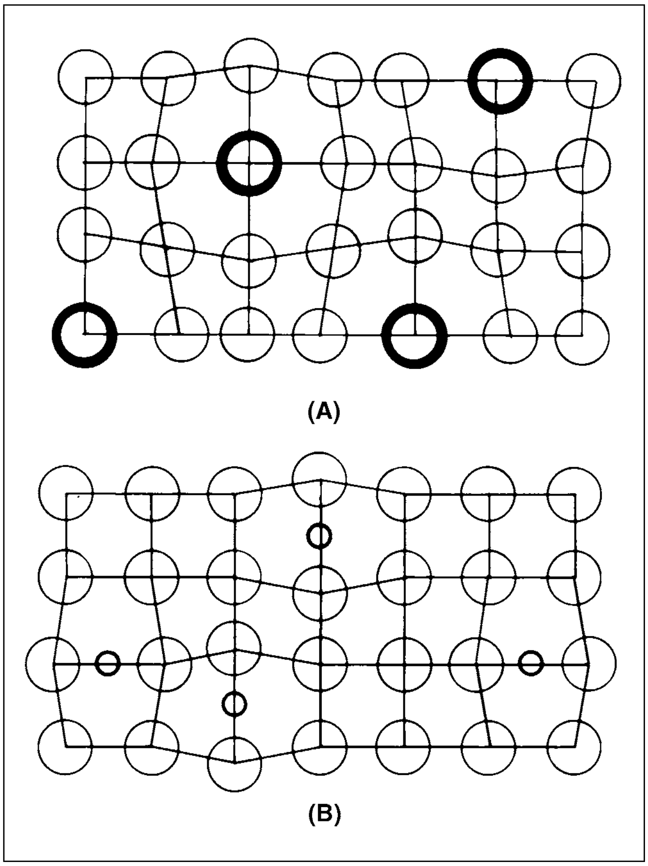


Figure 4.3—Schematic Illustration of (A) Substitutional and (B) Interstitial Solid Solutions

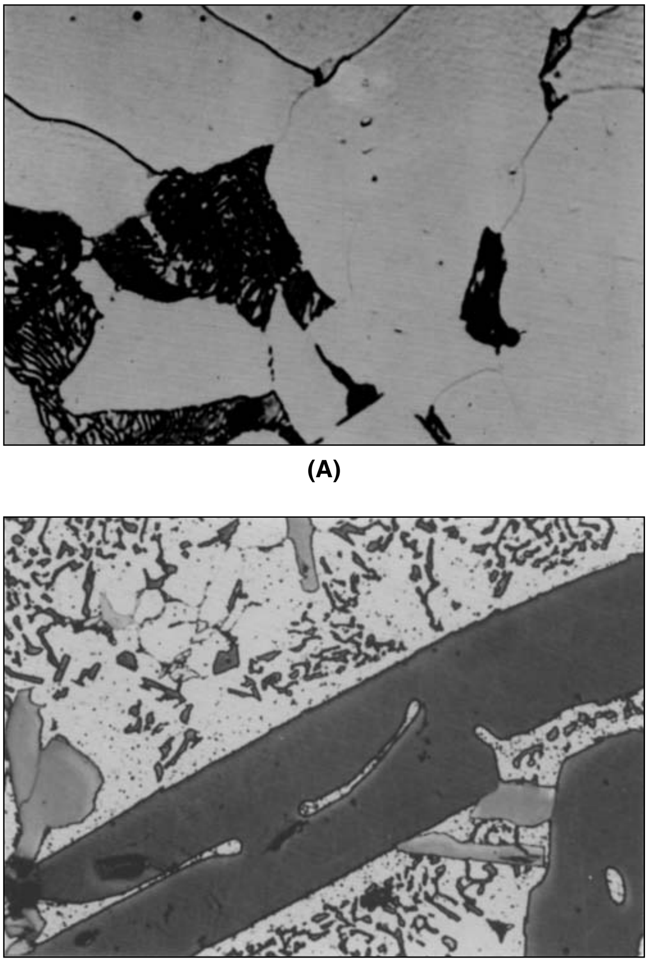


Figure 4.4—Multiphase Alloys: (A) Typical Microstructure of Two-Phase Pearlitic Low-Carbon Steel (Light Areas Indicate Ferrite; Dark Areas, Pearlite), 100X Magnification (before Reduction) and (B) Fine-Grain Aluminum Silicon Alloy Sample with Small Pearlite Patches, 100X Magnification (before Reduction)

Multiphase Alloys

Alloying atoms often do not dissolve completely, either substitutionally or interstitially, resulting in the formation of mixed atomic groupings (i.e., different crystalline structures) within a single alloy. In such an alloy, known as a *multiphase alloy*, each of the different crystalline structures is referred to as a *phase*. If an alloy is suitably polished and etched, these individual phases may be distinguished when viewed under a microscope at 50X to 2000X magnification. This process of polishing, etching, and examining metals at some magnification, known as *metallography,* is one of the techniques used to study the many characteristics of metals and alloys.

Figure 4.4 presents two examples of multiphase alloys. Figure 4.4(A) demonstrates the typical microstructure of low-carbon pearlitic steel. The light areas are ferrite, and the dark areas are pearlite. The latter structure is composed of two phases—ferrite and iron carbide. Figure 4.4(B) shows multiple phases within the grains of an aluminum-silicon alloy.

Most commercial metals consist of a primary or basic element (solvent) plus smaller amounts (solute) of one or more alloying elements. As explained above, the alloying elements are either intentionally added or residual (tramp) elements. Commercial metals can be single- or multiple-phase alloys. Each phase has its characteristic crystalline structure.

The overall arrangement of grains, grain boundaries, and phases occurring in a metal alloy is referred to as the *microstructure* of the alloy. The microstructure, which is largely responsible for the physical and mechanical properties of the metal, is affected by the metal's chemical composition, thermal treatment, and mechanical history. The thermal and mechanical effects of welding can alter the microstructure, but the changes are confined to the region of the base metal close to the weld. The metallurgical changes that occur in these regions, known as the *weld metal* and the *heat-affected zone (HAZ)*, can have a profound effect on the service performance of a weldment.

Many unique phenomena that affect the mechanical properties of an alloy at both low and high temperatures occur at the grain boundaries, where the arrangement of atoms is irregular. Because many vacancies, missing atoms, and other defects are found at the grain boundaries, the spaces between the atoms may be larger than normal, permitting individual atoms to move about with relative ease. Thus, the diffusion of elements (i.e., the movement of individual atoms) through the solvent structure generally occurs more rapidly at the grain boundaries than within the grains. The resulting disarray makes it easier for odd-sized atoms to segregate at the boundaries. This segregation frequently leads to the formation of undesirable phases that adversely affect the properties of a metal by reducing its ductility, increasing its susceptibility to cracking during welding or heat treatment, or reducing its corrosion resistance.

PHASE TRANSFORMATIONS

In the field of metallurgy, the term *phase transformation* (or *phase change)* is used to describe the transformation undergone by a material or a distinct portion (phase) of a metal with respect to its crystallographic structure.

Critical Temperature

Many metals change their crystallographic structure at specific temperatures. The temperature at which one phase is changed into another phase is known as the *critical temperature*. For example, at temperatures up to 1670°F (910°C), the crystalline structure of pure iron is body-centered cubic. From 1670°F to 2535°F (910°C to 1390°C), the structure is face-centered cubic, and from 2535°F (1390°C) to 2795°F (1535°C), the melting temperature, it is again body-centered cubic. This type of phase change in a crystalline structure in the solid state is known as an *allotropic transformation*. Other metals that undergo allotropic transformations include uranium, hafnium, titanium, zirconium, and cobalt. Chemical composition, the cooling rate, and the presence of stress influence the temperature at which the transformation takes place.

Metals also undergo a phase change when they melt or solidify. Pure metals melt and solidify at a single temperature. Alloys, on the other hand, usually melt and solidify over a range of temperatures. An exception to this rule is the eutectic composition of certain alloys, which is discussed below.

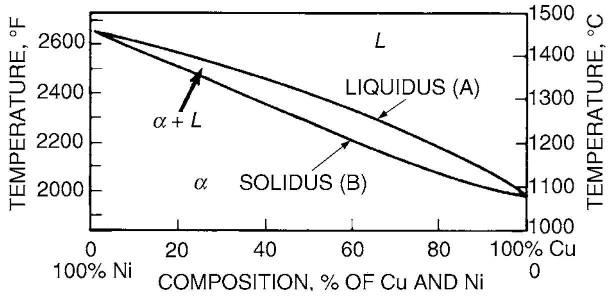
Phase Diagram

Metallurgical events such as phase changes and solidification are best illustrated by means of a phase diagram, which is sometimes referred to as an *equilibrium* or a *constitution diagram*. This graphical representation plots the stable phases for temperature versus composition for a metal at equilibrium. In metallurgy, the term *equilibrium* is used to refer to a condition of chemical, physical, thermal, mechanical or atomic balance for a given environment. The examination of a phase diagram of a given alloy system permits the determination of the phases present and the percentages of each phase for various alloy compositions at specified temperatures. Phase diagrams also furnish information regarding melting points, solubility, solidification, and the phase changes that tend to occur with a change in composition or temperature, or both. Phase diagrams are also an important tool in the field of the metallography of welding as they provide information about the microstructure of weldments.

As most published phase diagrams are based on two-component systems at equilibrium, they provide only an approximate description of commercial alloys, which have more than two components and reach equilibrium conditions only at high temperatures. Phase diagrams can be constructed for metal systems having more than two components, but these diagrams are complex and difficult to interpret. Nevertheless, phase diagrams are the best technique for studying most alloy systems.

A very simple phase diagram for the copper-nickel alloy system is shown in Figure 4.5. This is a binary system in which both elements are completely soluble in each other in all proportions at all temperatures in both the liquid and the solid states. As can be observed in this figure, phase diagrams are conventionally drawn with the alloy content plotted on the horizontal axis and temperature on the vertical axis. The extreme left-hand edge of Figure 4.5 represents 100% (pure) nickel (Ni), while the extreme right-hand edge represents 100% (pure) copper (Cu).

At temperatures above Curve A, termed the *liquidus* (the line on a phase diagram that indicates the temperature at which components begin solidifying during cooling or finish melting during heating), the only phase present is liquid metal. At temperatures below Curve B, called the *solidus* (the line on a phase diagram that indicates the temperature at which components finish



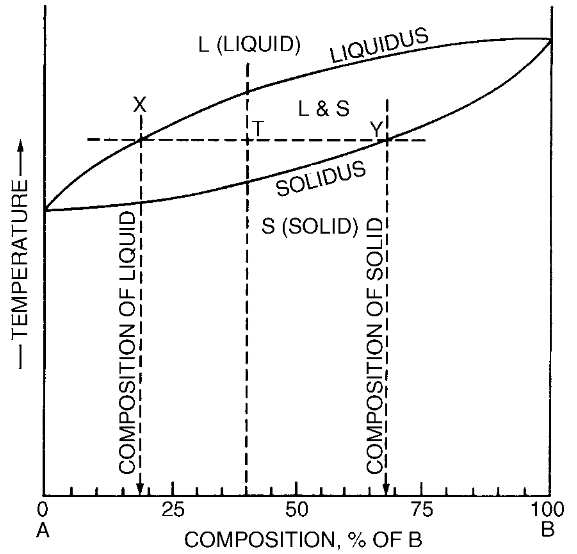
Key:
α = Solid solution of Cu and Ni
L = Liquid metal consisting of both Cu and Ni

Figure 4.5—Copper-Nickel Phase Diagram

solidifying during cooling or begin melting during heating), the only phase present is solid metal. All solid alloys in this diagram are homogeneous single-phase solid solutions because copper and nickel are completely soluble in each other in all proportions.

One important commercial alloy, 30% copper-70% nickel, remains solid up to 2425°F (1330°C), at which point it begins to melt. Melting is complete at 2490°F (1365°C). In the region between Curves A and B, solid and liquid phases coexist. Unlike pure metals, most alloys melt and freeze over a range of temperatures. In this system, only pure copper and pure nickel melt and freeze at a constant temperature.

The lever law can be applied to phase diagrams to derive useful information regarding the solidification process. When this law is applied at different temperature levels in the solidification range, it demonstrates that the composition of the solid phase changes during the interval of solidification over a falling temperature. Therefore, when the early dendrites (crystals with a tree-like structure) cool slowly enough to achieve equilibrium in the solidifying alloy, their composition changes, and they are richer in the metal with the higher melting point than in the solid formed at a lower temperature. Materials may actually exist in heterogeneous equilibrium unless diffusion occurs to remove this compositional difference in a state of so-called equilibrium. In fact, equilibrium is practically never achieved in commercial casting or fusion welding operations, and differences in both temperature and composition are present, as indicated by phase diagrams and as actually found in the alloy.[1] An example of the application of the lever law phenomenon to a phase diagram is illustrated in Figure 4.6.



When the hypothetical liquid alloy composed of 60% Metal A and 40% Metal B cools to the point designated as T on the dotted vertical line in the figure, the lever law is implemented by drawing a horizontal line (also dotted) through T and extending to the liquidus on the left with the solidus on the right. From the points at which the horizontal line intersects the solidus and the liquidus, vertical lines (also dotted) are dropped to the compositional scale on the abscissa. At temperature T, the amount of solid alloy formed and the liquid alloy still remaining are indicated by the relative workpieces of the line XY. The percentage of solid is indicated by the segment XT (i.e., percent solid = XT/XY [100]). The composition of the solid forming at temperature level T is found by noting where the vertical dotted line from Y intersects the abscissa (approximately 32% A/68% B). The remaining liquid, indicated by a similar line extending from X, consists of approximately 82% A/18% B.

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 4.2 and p. 302.

Figure 4.6—Application of the Lever Law to a Phase Diagram

The silver-copper system exhibits a more complex phase diagram. This diagram, presented in Figure 4.7, is used extensively in designing brazing alloys. The solid exists as a single phase in two areas of the diagram and as two phases in another area. The silver-rich phase is designated *alpha* (α), while the copper-rich phase is denominated *beta* (β). Both phases are face-centered cubic, but their chemical compositions and the crystal dimensions are different. In the region between the solidus and liquidus lines, the liquid solution is in equilibrium with either the α or β phase. Finally, the area labeled α + β contains grains of both alpha and beta.

1. Linnert, G. E., ed., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, pp. 301–302.

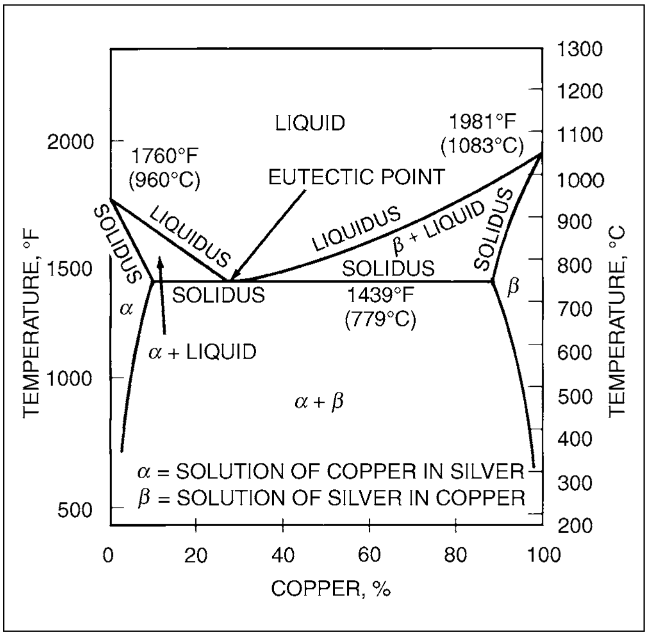


Figure 4.7—Silver-Copper Phase Diagram

In Figure 4.7, the boundary between the β and the $\alpha + \beta$ regions represents the solubility limit of silver in copper. The solubility increases with increasing temperature. This characteristic, which is typical for many alloy systems, makes it possible for some alloys to be precipitation hardened. Precipitation hardening is discussed further below.

This phase diagram, which also illustrates the eutectic point, can be produced when two components of a binary alloy system have partial solubility. A eutectic is a physical mixture of two or more phases. The number of phases equals the number of components in the alloy system. Alloys of eutectic composition solidify at a constant temperature. Eutectic compositions solidify differently than pure metals in that small quantities of the alpha and beta phases freeze alternately. For this reason, microstructures with a eutectic composition have a distinctive appearance.

EFFECTS OF DEFORMATION AND HEAT TREATMENT

Material deformation and different thermal processing can have varying effects on the material's mechanical and corrosion properties. Deformation and heat treatment can be performed separately or in combination, depending on the properties desired.

Strain Hardening

When metals are plastically deformed (e.g., cold rolled or forged) at room temperature, a number of changes take place in their microstructures. Each individual grain must change shape to achieve the overall deformation. As deformation proceeds, each grain becomes stronger, making it difficult to deform it further. This behavior is termed *strain hardening*.

Cold Working

Cold working involves the plastic deformation of a metal with the intent to change its shape and improve the mechanical properties at low temperatures. The effect of cold working on the strength and ductility of a metal is illustrated in Figure 4.8(A). When the metal is deformed below a critical temperature, the hardness and strength of the metal gradually increase, while the ductility decreases. The original properties of some metals can be partially or completely restored by heat treatment (annealing), as illustrated in Figure 4.8(B).

The microstructures of mildly deformed, heavily deformed, and stress-relieved steels are shown in Figures 4.9(A), (B), and (C), respectively. Several phenomena occur if the same metal is worked moderately, as in Figure 4.9(A), or severely, as in Figure 4.9(B), and then heated to progressively higher temperatures. At temperatures up to approximately 400°F (204°C), the residual stress level steadily declines, but virtually no change occurs in the microstructure or properties. From about 400°F to 450°F (204°C to 230°C), the residual stress decreases to a relatively low level, while the microstructure remains unchanged. The strength of the metal is still relatively high, and the ductility, while improved, is still rather low. The reduction in stress level and the improvement in ductility are attributed to the metallurgical phenomenon known as *recovery*, a reduction in crystalline stresses without any accompanying microstructural changes.

When cold-worked metal is heated to a temperature above 450°F (230°C), changes in the microstructure and mechanical properties can become apparent, depending on the material. In place of the deformed grains found in Figure 4.9(A) and Figure 4.9(B), a group of new grains form and grow, as shown in Figure 4.9(C). These grains consume the old grains, and eventually all signs of the deformed grains disappear. The new microstructure resembles that present prior to cold working, and the metal is now softer and more ductile than it was in the cold-worked condition. This process, termed *recrystallization*, is a necessary element of annealing, a heating and cooling process usually applied to induce softening and eliminate stresses.

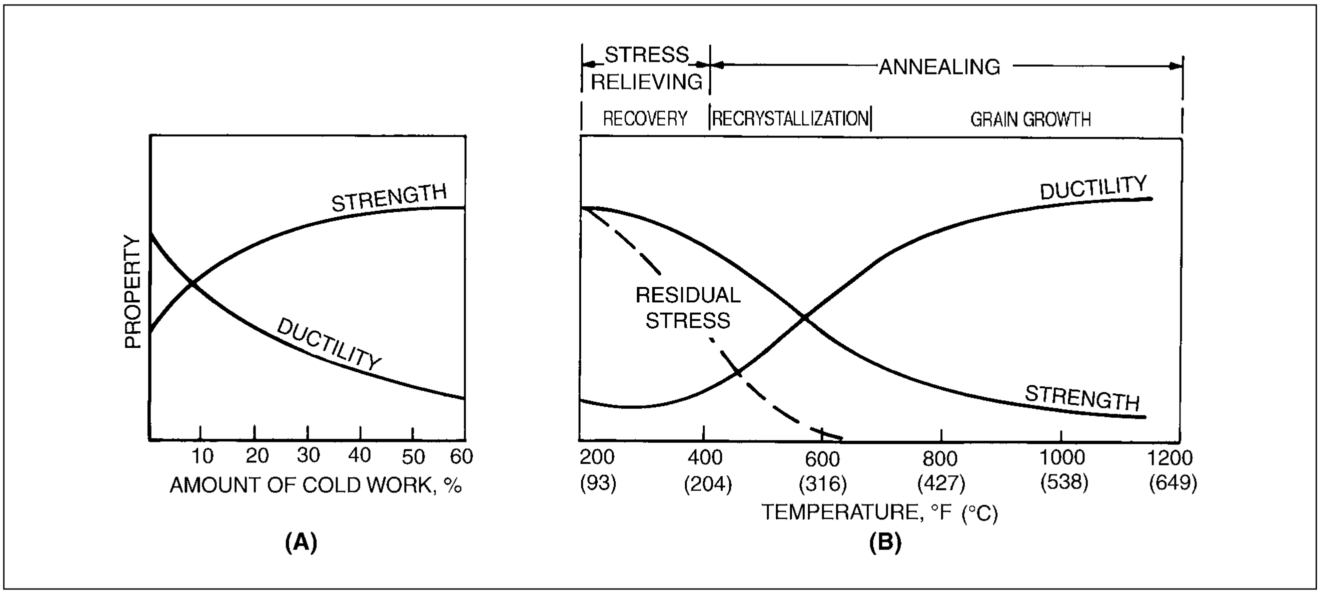


Figure 4.8—(A) Effect of Cold Work on the Strength and Ductility of Steel and (B) Effect of Posterior Cold-Work Heat Treatment on the Strength and Ductility of Steel

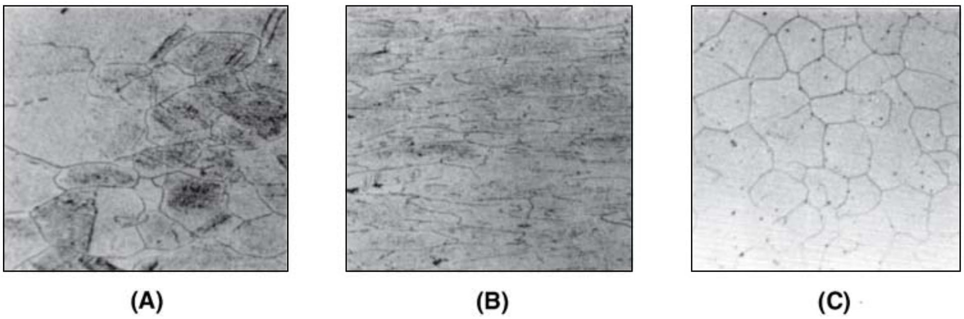


Figure 4.9—Grain Structure: (A) Lightly Cold-Worked; (B) Severely Cold-Worked; (C) Cold-Worked and Recrystallized

Phase Transformations in Iron and Steel

Steel and other iron alloys are the most common commercial alloys in use. The properties of iron and steel are governed by the amount of solute, usually carbon, and the phase transformations they undergo during processing. An understanding of these transformations is therefore essential to the successful welding of these metals.

Pure iron solidifies as a body-centered cubic structure known as *delta (δ) iron* or *delta ferrite*. Upon further cooling, it transforms into a face-centered cubic structure termed *gamma (γ) iron* or *austenite*. The austenite subsequently transforms back into a body-centered cubic structure known as *alpha (α) iron* or *alpha ferrite*.

Steel is an iron alloy that contains less than 2% carbon. The presence of carbon alters the temperatures at which solidification and phase transformations take place. The addition of other alloying elements also affects the transformation temperatures. Variations in carbon content have a profound effect on both the transformation temperatures and the proportions and distributions of the various phases—austenite (γ), ferrite (α), and cementite (Fe_3C), the latter being a compound of iron and carbon, as shown in the iron-carbon phase diagram presented in Figure 4.10.

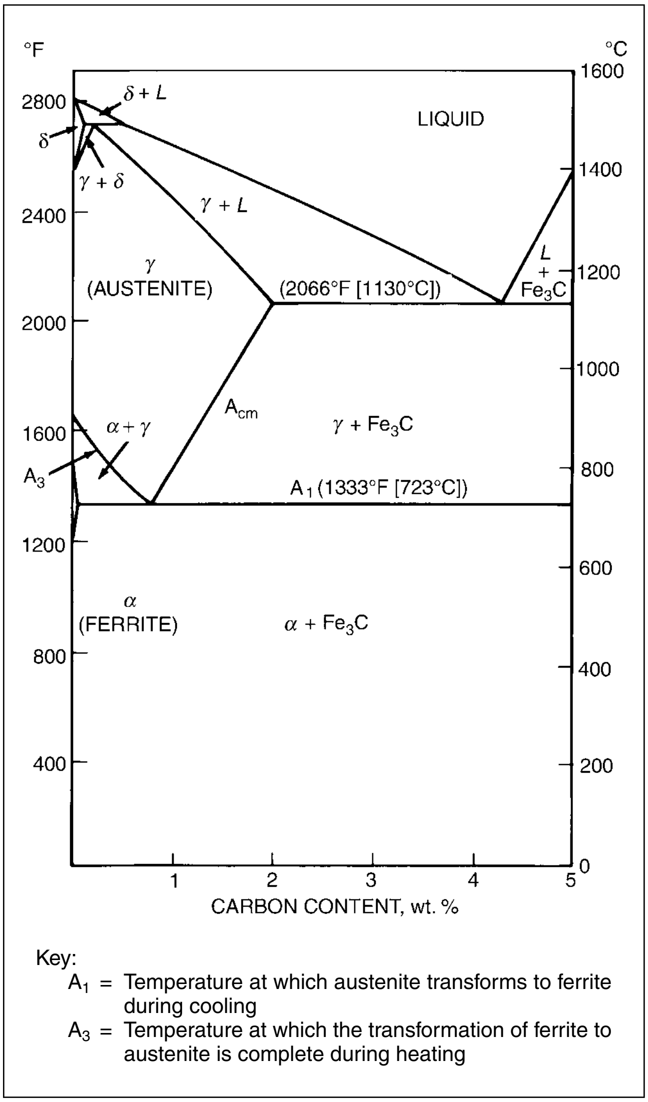


Figure 4.10—Iron-Carbon Phase Diagram

Delta Ferrite to Austenite. The transformation of delta ferrite to austenite occurs at 2535°F (1390°C) in essentially pure iron. However, in steel, the transformation temperature increases with increasing carbon content to a maximum of 2718°F (1492°C). Steels with more than 0.5% carbon solidify directly to austenite at a temperature below 2718°F (1492°C). Therefore, delta ferrite does not exist in these steels.

Austenite to Ferrite Plus Iron Carbide. The transformation of austenite to ferrite plus iron carbide that occurs during cooling is one of the most important transformations in steel. Control of this transformation is the basis for most of the heat treatments used for hardening steel. This transformation occurs in essentially pure iron at 1670°F (910°C). In steel with increasing carbon content, however, the transformation takes place over a range of temperatures between boundaries A_3 and A_1, as shown in Figure 4.10. The upper limit of this temperature range (A_3) varies from 1670°F (910°C) to 1333°F (723°C). For example, the A_3 of a 0.10% carbon steel is 1600°F (870°C), while for a 0.50% carbon steel, it is 1430°F (775°C). Thus, the presence of carbon promotes the stability of austenite at the expense of delta and alpha ferrite at both high and low temperatures. The lower temperature of the range (A_1) remains at 1333°F (723°C) for all plain carbon steels, regardless of the carbon level.

Austenite can dissolve up to 2.0% of carbon in solid solution, whereas ferrite can dissolve only 0.025%. At the A_1 temperature, austenite transforms to ferrite and the intermetallic compound of iron and carbon known as *cementite* (Fe_3C). Ferrite and cementite in adjacent platelets form a lamellar structure. This characteristic lamellar structure, known as *pearlite*, is shown in Figure 4.11.

Most of the common alloying elements added to steel further alter the transformation temperatures. Room temperature microstructures of iron-carbon alloys at the equilibrium conditions specified in Figure 4.10 include one or more of the following constituents:

1. Ferrite, a solid solution of carbon in alpha iron;

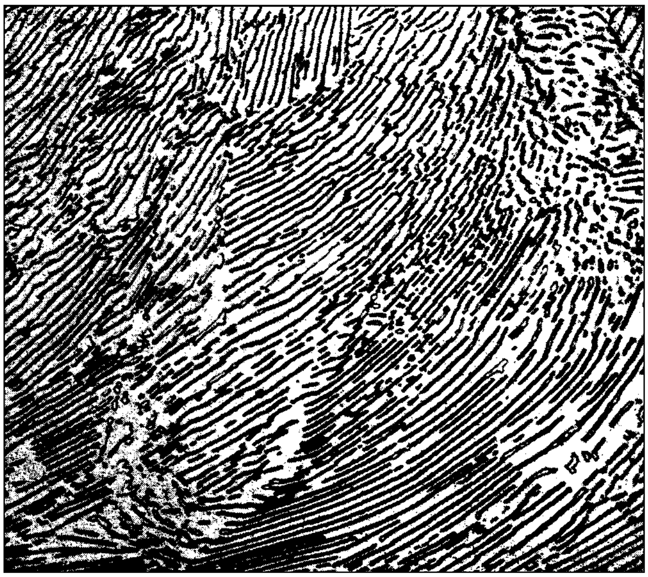


Figure 4.11—Typical Lamellar Appearance of Pearlite, 1500X Magnification (before Reduction); Etchant: Picral

2. Pearlite, a mixture of cementite and ferrite that forms in plates or lamellae; and
3. Cementite, iron carbide (Fe_3C) present in pearlite or as massive carbides in high carbon steels.

When carbon steels are slowly cooled from the austenitic temperature range, the relative amounts of these three constituents present at room temperature depend on the chemical composition. However, austenite decomposition is suppressed when the cooling rate is accelerated. When transformation begins, it progresses more rapidly, and larger volumes of pearlite are formed.

As the cooling rate is further increased, the pearlite lamellae become finer as the platelets are closely spaced. At fast cooling rates, still lower transformation temperatures are encountered, and a feathery distribution of carbides in ferrite is formed instead of pearlite. This feathery arrangement of shear needles with fine carbides in a ferrite matrix is known as *bainite*. It has significantly higher strength and hardness and lower ductility than fine pearlitic structures. With very fast cooling rates (severe quenching), martensite forms.

Martensite is the hardest austenite decomposition product. When the cooling rate is fast enough to form 100% martensite, no further increases in hardness can be achieved by faster quenching. A typical martensitic microstructure is shown in Figure 4.12. The decomposition of austenite is an important consideration in the welding of steel alloys because the weld metal and workpieces of the heat-affected zone (HAZ) undergo this transformation.

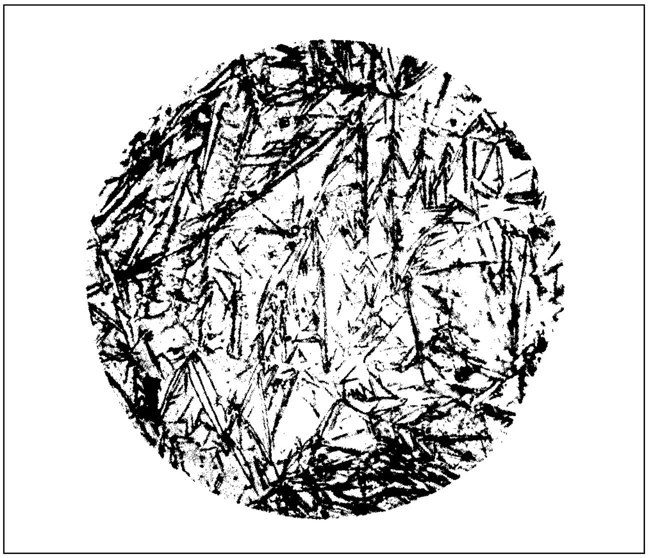


Figure 4.12—As-Quenched Martensite, 500X Magnification (before Reduction), Etched

Certain commonly used terms in heat treating involve the rate at which austenite is cooled to room temperature. The following treatments are listed in the order of increased cooling rates from above the A_3 temperature:

1. Furnace annealing (slow furnace cooling),
2. Normalizing (cooling in still air),
3. Oil quenching (quenching in an oil bath),
4. Water quenching (quenching in a water bath), and
5. Brine quenching (quenching in a salt brine bath).

If a specific steel were treated in the order of (1) to (5) above, its hardness and tensile strength would become increasingly greater until the microstructure was composed of nearly 100% martensite.

Isothermal Transformation Diagram

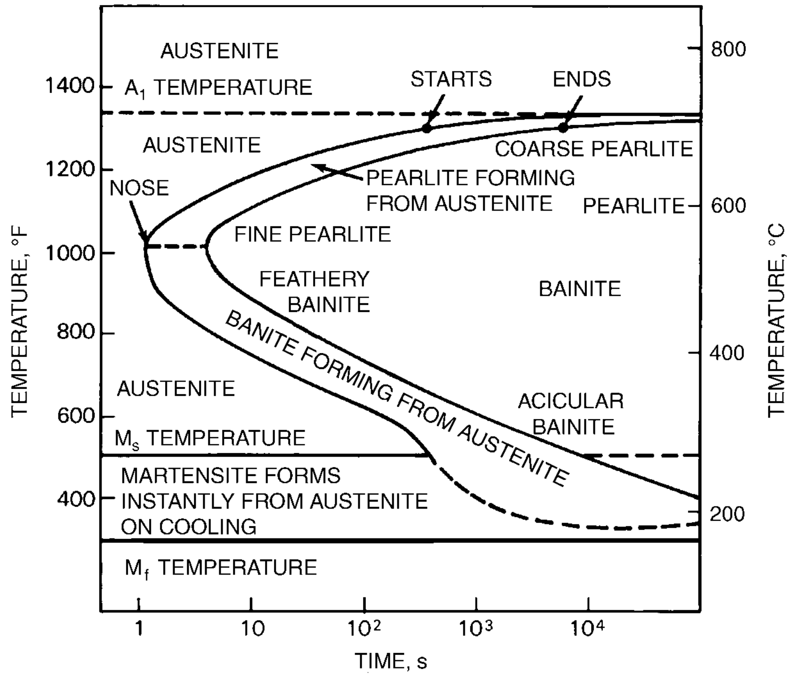
Although the iron-carbon phase diagram is very useful, it provides no information about the transformation of austenite to any structure other than that at equilibrium and furnishes no details on the suppression of the austenite transformation. Moreover, it fails to demonstrate the relationship between the transformation products and the transformation temperature.

A more practical diagram is the isothermal transformation or time-temperature-transformation (TTT) diagram. This diagram graphically describes the time delay and the reaction rate of the transformation of austenite to pearlite, bainite, or martensite. It also identifies the temperature at which these transformations take place. A TTT diagram for 0.80% plain carbon steel is presented in Figure 4.13.

To create the TTT diagram shown in Figure 4.13, samples of 0.80% carbon steel were austenitized at 1550°F (845°C). The samples were then quenched in molten salt baths to a variety of temperatures below 1300°F (700°C). Each specimen was held at its chosen reaction temperature for a specified length of time and then removed from the salt bath, quenched to room temperature, polished, etched, and examined under a microscope. Metallographic examination revealed the amount of austenite that transformed in the salt bath. The reaction start times and completion times were plotted as shown in Figure 4.14.

In Figure 4.13, it can be observed that austenite begins to transform after about 480 seconds (8 minutes) at 1300°F (700°C). The reaction is complete after about 7200 seconds (2 hours). At 1000°F (540°C), which is the "nose" of the curve, the reaction begins after an elapsed time of only one second and proceeds rapidly to completion in about seven seconds.

At temperatures below the nose, the transformation products change from pearlite to bainite and martensite



Key:
A_1 = Temperature at which austenite begins to form during heating
M_s = Temperature at which the transformation of austenite to martensite begins during cooling
M_f = Temperature at which the transformation of austenite to martensite is complete during cooling

Figure 4.13—Isothermal Transformation Diagram of a Eutectoid Plain Carbon Steel

with their characteristic feathery and acicular structures. As the carbon and alloy content increases, the TTT curve shifts to the right. When the curves move to the right, the steels transform into martensite at slower cooling rates. These steels are said to have higher hardenability.

In summary, steels with the best weldability are characterized by phase diagrams having the nose to the left as much as possible. Standards[2] such as *Structural Welding Code—Steel,* AWS D1.1,[3] consider hardenability to be related to weldability. For this reason, the carbon content and the alloy content are tailored to minimize the formation of martensite.

Continuous Cooling Transformation Diagrams

In most heat treating processes and in welding, austenite transforms during the cooling process. A diagram referred to as the *continuous cooling transformation (CCT) diagram* is used to supply information about the transformation of austenite during cooling. The information provided in CCT diagrams is used in the

2. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

3. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society.

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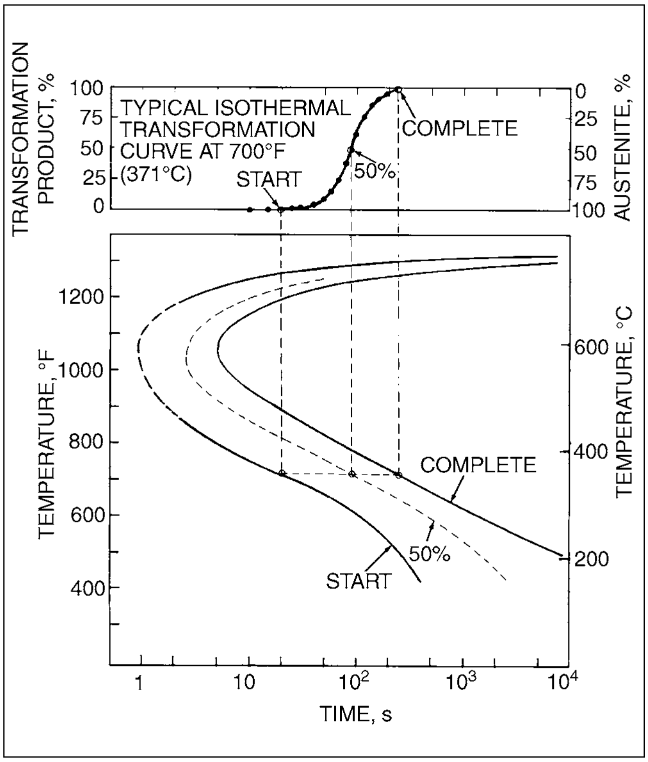

Figure 4.14—Method of Constructing the TTT Diagram

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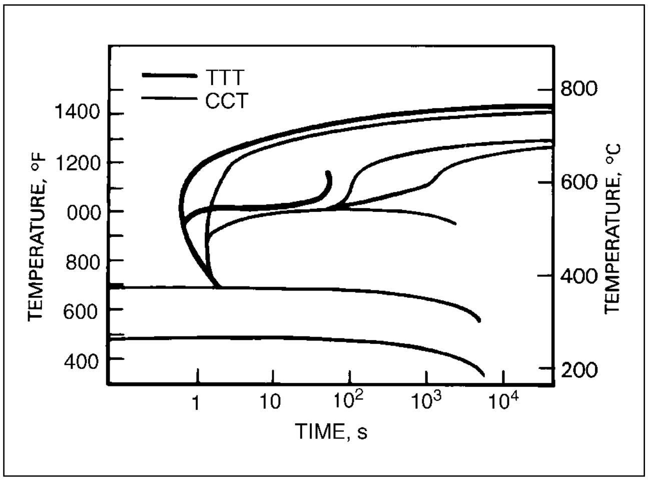

Figure 4.15—CCT and TTT Diagrams for 8620-Type Steel

qualification of the welding procedure and as the basis for the design code.

The most important difference between the TTT and the CCT diagrams is that in the CCT diagram the start of the transformation during continuous cooling takes place after a longer delay time and at a lower temperature than would be predicted using a TTT diagram. In other words, the curves of a CCT diagram are displaced downward and toward the right. For purposes of comparison, a CCT and a TTT diagram for AISI 8630 steel are shown together in Figure 4.15.

TRANSFORMATION OF STEEL AUSTENITIZED BY THE WELDING PROCESS

Isothermal diagrams provide a means for estimating the microstructures that are produced in a steel heat-affected zone during welding. Therefore, they serve as the basis for welding plans based on the metallurgical characteristics of the steel. However, TTT diagrams fail to provide an exact basis for predicting microstructures inasmuch as significant differences exist between the austenite transformation characteristics developed during a welding thermal cycle and those resulting from a heat treating cycle.

In the case of heat treatment, a steel is held at temperature for a sufficient time to dissolve the carbides and develop a homogeneous austenitic phase having a relatively uniform grain size. In a weld thermal cycle, the austenitizing temperature (peak temperature) varies from near the melting point to the lower critical temperature, and the duration of the cycle is very short relative to the normal soaking times in heat treating cycles.

At high peak temperatures near the weld interface, diffusion is more rapid, and solute atoms (especially carbon) disperse uniformly in the austenite.[4] In addition, austenite grain growth occurs. At lower peak temperatures slightly above the austenite transformation temperature, carbides may not be completely dissolved in the austenite. Furthermore, the solute atoms that do dissolve because of the relatively low temperature may not diffuse far from the original site of the carbide. Thus, at these lower peak temperatures, the austenite contains areas of high-alloy content (i.e., the steel is enriched) and low-alloy content (i.e., the steel is impoverished). In addition, the austenite possesses a fine-grained microstructure. At intermediate peak temperatures, the homogeneity and the grain size of austenite are between these extremes.

4. The relationship between the peak temperature and the distance from the weld interface is discussed in Chapter 3 of this volume.

Upon cooling, the austenitic decomposition temperature and decomposition products depend upon the local chemical composition and the grain size as well as the cooling rate. Nonhomogenous austenite has a different transformation behavior than homogenous austenite.

Two transformation diagrams of the same heat of Ni-Cr-Mo steel are shown in Figure 4.16. One diagram characterizes the isothermal transformation of austenite after a 30-minute soak at 1550°F (840°C). The other diagram characterizes the transformation of austenite during the cooling portion of a weld thermal cycle to a peak temperature near the weld interface (2400°F [1310°C]). Marked differences in the transformation characteristics exist for the two thermal conditions.

In the microstructure in the heat-affected zone, the start of the pearlite and bainite transformations was delayed by a factor of 6, and the martensite start (M_s) temperature was depressed by 90°F (50°C). If the peak temperature of the weld thermal cycle were reduced to below 2400°F (1315°C), the austenite would be less homogeneous, have a finer grain size, and exhibit a different transformation behavior upon cooling. Thus, it is obvious that austenitizing conditions have a significant effect on transformation characteristics.

Factors Affecting the Transformation of Austenite

Chemical composition, austenitic grain size, and the degree of homogeneity of the austenite are important factors in determining the austenite transformation of steels. All normal transformations in solid steel (above the temperature at which martensite forms) take place by the process of nucleation and grain growth. New phases form at certain favorable locations—usually at grain boundaries—and grow in volume until the transformation is complete.

The composition of the steel is most important in determining transformation behavior. Carbon, nickel, manganese below 1%, silicon below 1-1/2%, and copper move the transformation curve to the right but do not change its shape. Thus, the TTT diagram of a plain carbon steel, which is shown in Figure 4.17, is similar to that of a nickel-alloy steel except that the decomposition of the austenite begins and ends later for the nickel steel. This can be seen in Figure 4.18. Chromium, molybdenum, vanadium, and other strong carbide-forming elements move the curve to the right as well, but they also change the shape of the curve. This phenomenon can be observed in Figure 4.19.

Only a few alloying elements move the lines of the transformation diagram to the left. Examples include cobalt and tellurium, neither of which is normally used in carbon and low-alloy steels.

Pearlite nucleates at austenitic grain boundaries. Therefore, fine-grained austenite provides many more

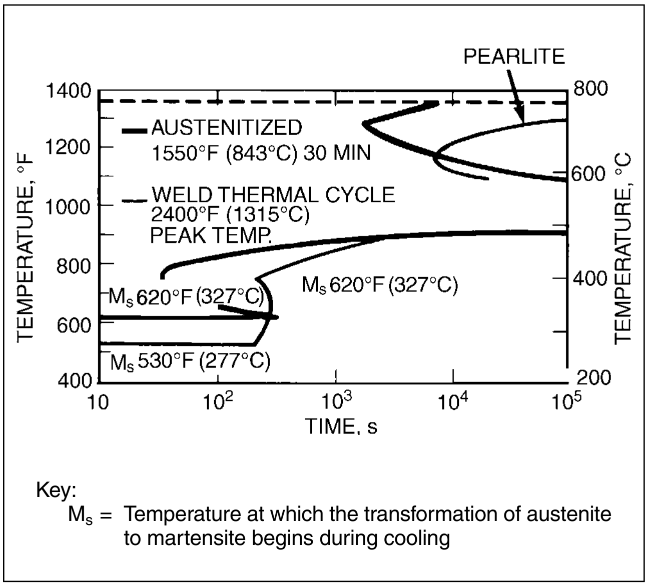

Figure 4.16—CCT Diagrams for a Heat-Treated Bar and a Simulated Weld Thermal Cycle

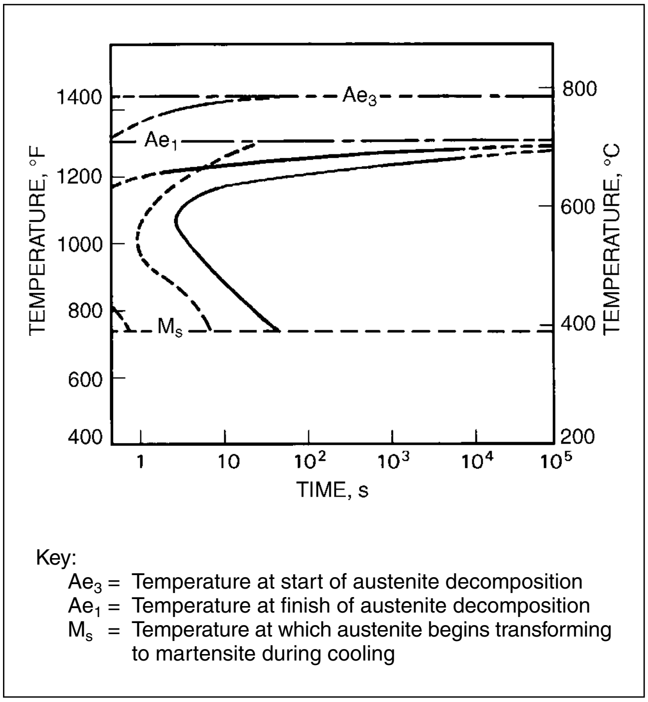

Figure 4.17—TTT Diagram for a 0.35% Carbon-0.37% Manganese-Nickel Steel

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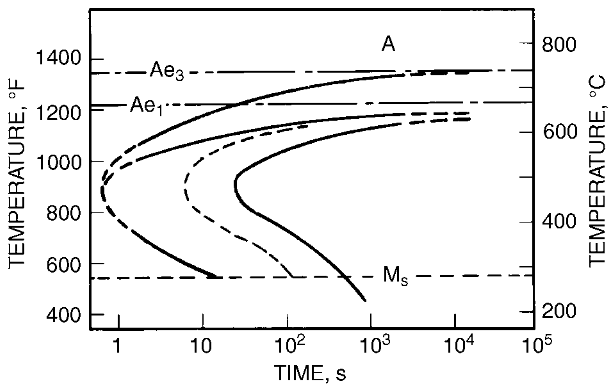

Key:
Ae$_3$ = Temperature at start of austenite decomposition
Ae$_1$ = Temperature at finish of austenite decomposition
M$_s$ = Temperature at which austenite begins transforming to martensite during cooling

Figure 4.18—TTT Diagram for a 0.37% Carbon-0.68% Manganese Steel

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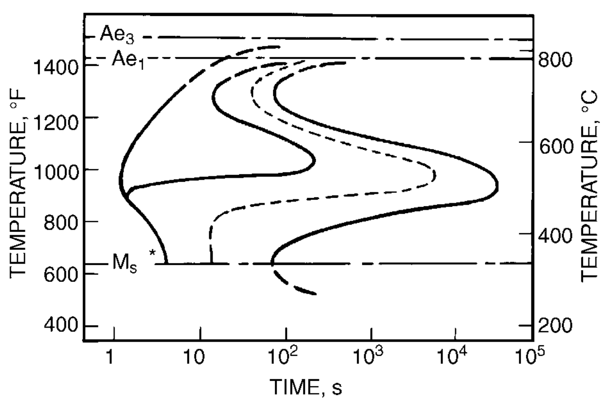


*CALCULATED TEMPERATURE

Key:
Ae$_3$ = Temperature at start of austenite decomposition
Ae$_1$ = Temperature at finish of austenite decomposition
M$_s$ = Temperature at which austenite begins transforming to martensite during cooling

Figure 4.19—TTT Diagram for a High-Carbon 2% Chromium Steel

nucleation sites than coarse-grained austenite does. As a result, more nuclei form, and the austenite transforms more rapidly. In contrast, bainite formation seems to be little affected by austenite grain size.

As previously noted, transformation behavior is related to the chemical composition of the local austenite. If the austenite is not homogeneous, the alloy-enriched areas become higher alloyed and therefore have higher hardenability than the impoverished areas do.

Undissolved carbides promote the transformation of austenite in two ways. First, they do not contribute to the alloy content of the austenite. Secondly, they serve as nucleation sites for austenite decomposition.

The martensite start temperature, M_s, and the martensite finish temperature, M_f, are generally lowered by the addition of alloying elements to steel. In some cases, the M_f point may be below room temperature, in which case some austenite is retained in the steel after cooling to room temperature. The M_s and M_f temperatures are also influenced by the homogeneity of the austenite, but grain size seems to have little effect.

HARDENABILITY

The concept of hardenability constitutes another method of describing the transformation of austenite in various steels. Hardenability characteristics are important to the welding engineer inasmuch as they determine the extent to which a steel hardens during welding. Hardenability should not be confused with hardness, which is a function of the carbon content of the steel, as illustrated in Figure 4.20.

On the other hand, hardenability is a measure of the amount of martensite that forms in the microstructure upon cooling. Certain steels that have high hardenability form martensite when they are cooled in air. Others with low hardenability require rapid cooling rates to transform to martensite.

Tempering of Martensite

Inasmuch as martensite can be quite brittle in the as-quenched condition, it is generally unsuitable for engineering applications. However, a tempering heat treatment can effectively increase its ductility and toughness while only moderately reducing its strength.

Tempering consists of reheating the steel to an appropriate temperature (always below the A_1) and holding it at that temperature for a short time. This heat treatment allows the carbon to precipitate in the form of tiny carbide particles. The resulting microstructure is referred to as *tempered martensite*. Any desired compromise between hardness and toughness can be

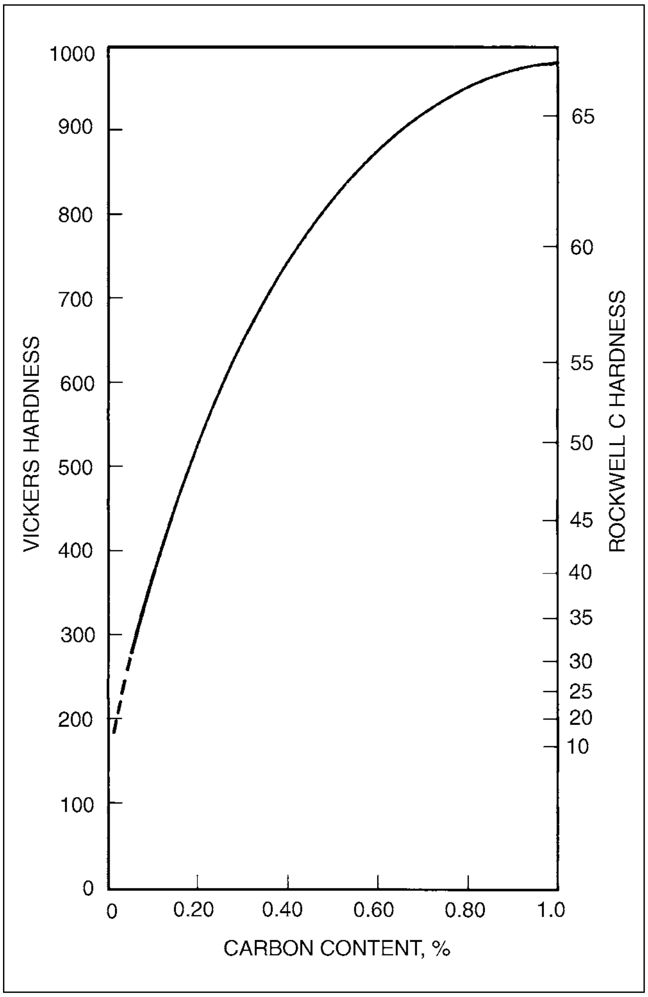


Figure 4.20—Effect of Carbon on the Maximum Hardness of Martensite

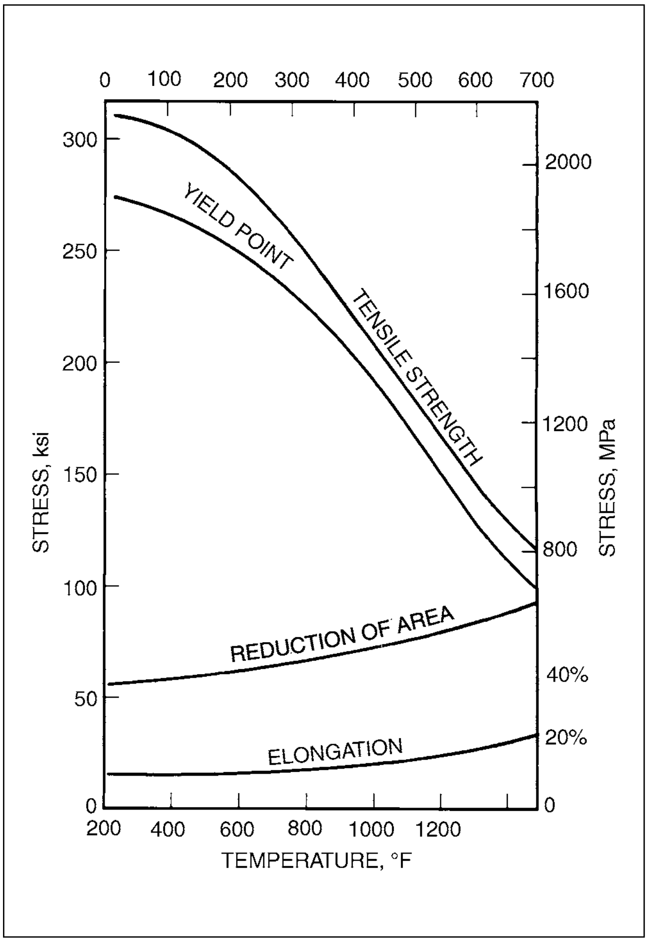


Figure 4.21—Effect of Tempering Temperature on the Strength and Ductility of a Chromium-Molybdenum Steel (AISI 4140)

obtained by choosing the proper tempering temperature and time. A higher tempering temperature results in a softer, tougher steel. The effect of tempering temperature on the mechanical properties of quenched AISI 4140 chromium-molybdenum (Cr-Mo) steel is shown in Figure 4.21.

Quenching and tempering are frequently used to enhance the properties of the steels used in machinery, pressure vessel, and structural applications. Quenched and tempered low-alloy steels exhibit high yield and tensile strengths, high yield-to-tensile strength ratios, and improved notch toughness compared to the same steel in the hot rolled, annealed, or normalized condition.

OTHER CHANGES IN GRAIN STRUCTURE

Fine-grained metals generally have better mechanical properties, making them suitable for service at room temperature and below. Conversely, coarse-grained metals generally perform better at high temperatures.

A fine grain size is desirable for improved toughness and ductility. Steel forgings and castings are frequently normalized specifically to produce grain refinement. The austenitic grain size of a steel depends on the austenitizing temperature and the duration of time the material is held at this temperature. Grain refinement occurs when a steel that will transform is heated to a temperature slightly above the A_3 temperature and is subsequently cooled to room temperature.

At higher austenitizing temperatures, that is, over 1832°F (1000°C), steels usually develop a coarse austenitic grain structure. Coarse-grained steels are usually inferior to fine-grained steels in strength, ductility, and toughness.

PRECIPITATION HARDENING

Precipitation hardening results from the precipitation of a constituent from a supersaturated solid solution. Precipitation hardening, also termed *age hardening*, is another method used to develop high strength and hardness in some steels. It is also important in the hardening of nonferrous alloys.

The principles of precipitation hardening are illustrated in Figures 4.22 and 4.23. As demonstrated in Figure 4.22, when a two-phase alloy of composition X is heated to temperature T_1, the β phase dissolves into the α phase. When the alloy is quenched rapidly to room temperature, the α phase has insufficient time to transform to the β phase. The resulting single-phase alloy is homogeneous and relatively soft.

When the alloy is reheated to temperatures between T_2 and T_4 for a time, the β phase forms as fine precipitates within the grains. The fine β precipitates in the grains can significantly strengthen the alloy, as shown in Figure 4.23. The mechanical properties of the alloy depend on the pre-age processing, the aging temperature, and time. It is also important to note that excessive temperature or time at temperature does not promote the development of maximum strength, hardness, or corrosion resistance.

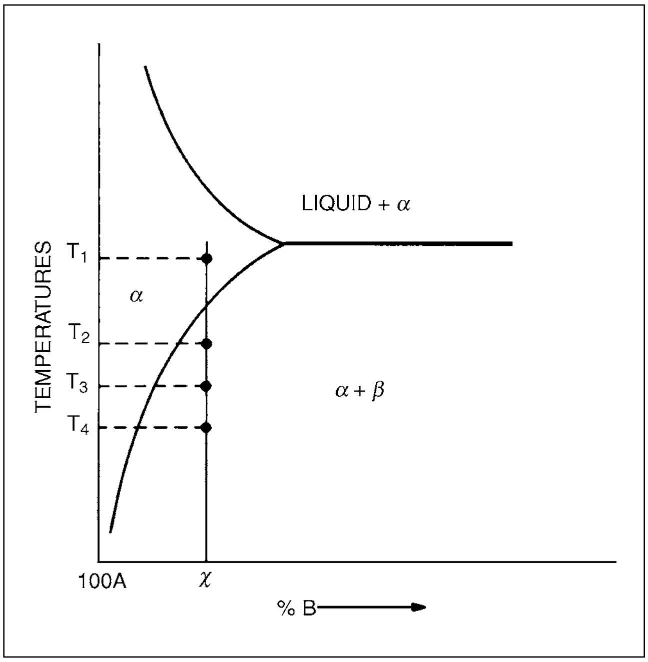


Figure 4.22—Phase Diagram of a Precipitation Hardening System

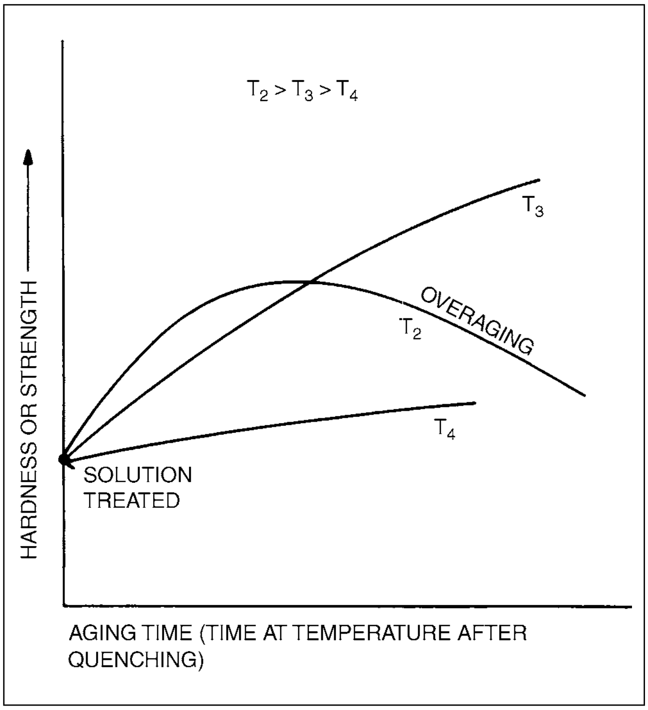


Figure 4.23—Effect of Aging Time and Temperature on the Hardness of a Precipitation Hardening System

METALLURGY OF WELDING

Welding is a complex metallurgical process involving melting and solidification, surface phenomena, and gas-metal and slag-metal reactions. These reactions occur more rapidly during welding than during metal manufacturing, casting, or heat treatment. A basic understanding of the weldments' processing history is necessary if good results are to be achieved.

THE WELDED JOINT

A welded joint consists of weld metal (which has been melted), heat-affected zones, and unaffected base metals. The metallurgy of each weld area is related to the compositions of the base and weld metals, the welding process, and the procedures used. Typical weld metals solidify rapidly and have a fine-grained dendritic microstructure. The weld metal is an admixture of melted base metal and deposited filler metal, if used. Some welds are composed of remelted base metal only. These are known as *autogenous welds*. Examples of autogenous welds are those produced by means of resistance, gas tungsten arc, and electron beam welding without filler metal. In most arc welding processes, however, filler metal is added.

To achieve mechanical and physical properties that nearly match those of the base metal, the weld metal as modified by the addition of filler metal is often similar in chemical composition to the base metal. This is not a universal rule, and sometimes the composition of the weld metal is deliberately designed to differ significantly from that of the base metal. The intent is to produce a weld metal having properties compatible with the base metal. Therefore, variations from the base metal composition are common in filler metals.

When a weld is deposited, the first grains to solidify initiate growth off the unmelted base metal, maintaining the same crystal orientation as that of the base metal grain off which they have grown. Depending upon the rates of composition and solidification, the weld solidifies in a cellular or a dendritic growth mode. Both modes cause segregation of alloying elements. Consequently, the weld metal is almost always less homogeneous than the base metal. Cellular and dendritic growth modes and the resulting segregation patterns are illustrated in Figure 4.24.

Adjacent to the weld metal is the heat-affected zone (HAZ), the portion of the base metal that has not been completely melted but whose microstructure or mechanical properties have been altered by the heat of

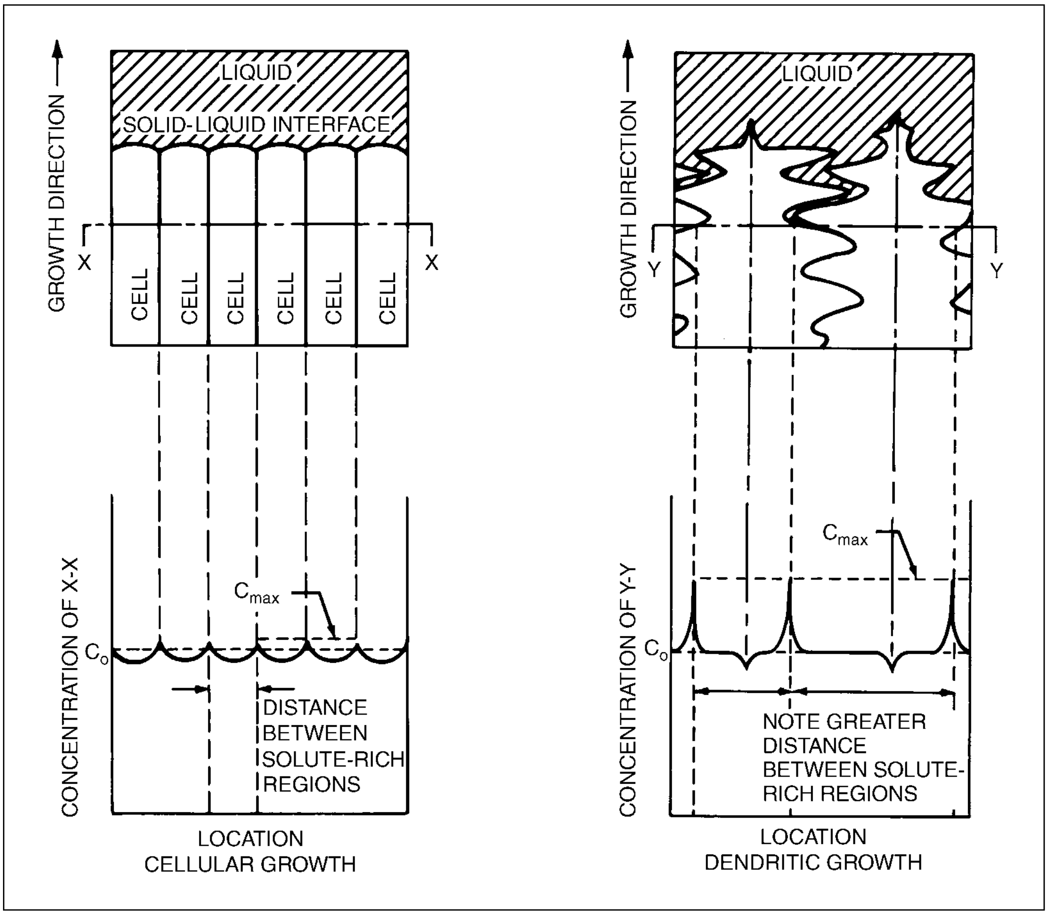


Figure 4.24—Schematic of Solute Distribution for Cellular and Dendritic Growth

welding. The width of the heat-affected zone is a function of the heat input. The heat input varies with different welding processes as well as with different variations of the same process.[5]

The third component of a welded joint is the unaffected base metal. This is the material to be joined. The weld metal and the heat-affected zone must be compatible with the base metal if a successful weld is to be produced. When the base metals are simple alloys that achieve their strength by alloy strengthening alone, the welding process can usually produce weld metals and heat-affected zones with compatible properties. When the base metals are strengthened by complex heat treatments or mechanical deformation, it may be difficult to produce weldments that are completely compatible.

The three constituents of a weld—the weld metal, the heat-affected zone, and the base metal—are discussed in further detail below.

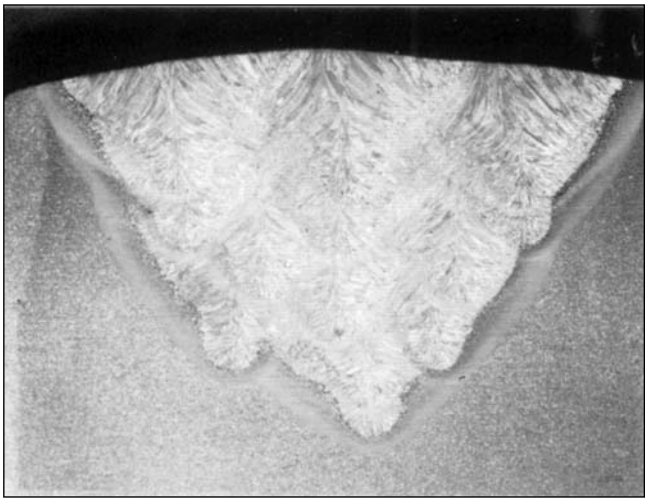


Figure 4.25—Macrostructure of a Low-Alloy Steel Weld

Weld Metal

The microstructure of weld metal is markedly different from that of base metal of similar composition, as shown in Figure 4.25. The difference in microstructure is not related to chemical composition, but to the differing thermal and mechanical histories of the base and weld metals.

The structure of the base metal is a result of a hot-rolling operation and multiple recrystallization of the hot-worked metal. In contrast, the weld metal has not been mechanically deformed. It therefore has an as-solidified structure. This structure and its attendant mechanical properties are a direct result of the sequence of events that occurs as the weld metal solidifies. These events include the reactions of the weld metal with gases near the weld and with nonmetallic liquid phases (slag or flux) during welding and those that take place in the weld after solidification.

Solidification. The unmelted portions of grains in the heat-affected zone at the solid-liquid interface serve as an ideal substrate for the solidification of the weld metal. Metals grow more rapidly in certain crystallographic directions. Therefore, favorably orientated grains grow for substantial distances, while the growth of grains that are less favorably oriented is blocked by the faster-growing grains. For this reason, weld metal often exhibits a columnar macrostructure in which the grains are relatively long and parallel to the direction of heat flow. This structure is a natural result of the influence of favorable crystal orientation, given the competitive nature of solidification grain growth.

Weld metal solidification for most commercial metals involves the microsegregation of the alloying and residual elements. This action is associated with and in large measure responsible for the formation of dendrites. A dendrite is a structural feature that reflects the complex shape taken by the liquid-solid interface during solidification, as shown in Figure 4.24.

As the primary dendrites solidify, solutes that are more soluble in the liquid are rejected by the solid material and diffused into the remaining liquid, lowering the freezing point. As the solute alloys concentrate near the solid-liquid interface, crystal growth is arrested in that direction. The grains then grow laterally, producing the dendrite arms characteristic of as-solidified metals. Many dendrites may grow simultaneously into the liquid from a single grain during solidification. Each of these dendrites has the same crystal orientation, and they are all part of the same grain. A solute-rich network exists among the dendrites in the final structure, as indicated in Figure 4.24. The weld metal structure appears coarse at low magnification because only the grain structure is visible. At high magnification, a fine dendritic structure is exhibited, as can be observed in Figure 4.26.

The spacing between dendrite arms is a measure of alloy segregation. Spacing is determined by the rate of solidification. The more rapid the solidification, the more closely spaced the dendrites will be. The general tendency is for weld-metal grain size to increase with heat input, but no fixed relationship exists. Grain size may also be influenced by nucleating agents, vibration,

5. For further information, see Chapter 2, "Physics of Welding," in this volume.

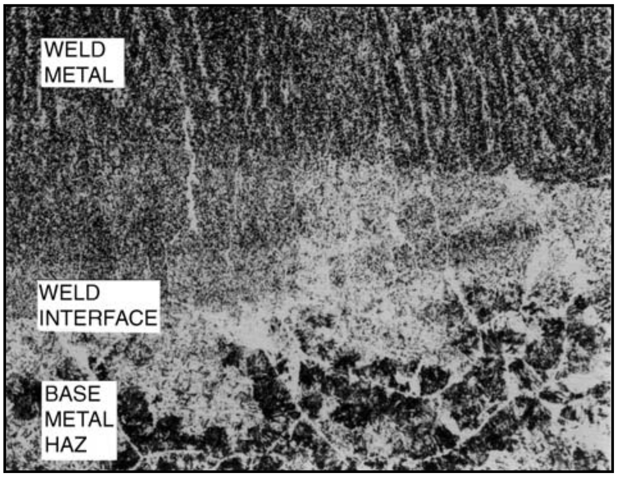


Figure 4.26—Microstructure of the Weld Metal and Heat-Affected Zone

or other process variables, whereas the dendrite arm spacing is exclusively a function of solidification rate, which is controlled by heat input.[6]

Gas-Metal Reactions. Gas-metal reactions depend on the presence of one or more reactive gases—hydrogen, oxygen, or nitrogen—in the shielding atmosphere. These elements have various sources.

The sources of hydrogen are many, though the most common source is air. In shielded metal arc welding (SMAW) and submerged arc welding (SAW), hydrogen may be present as water in the electrode coating and the loose flux. Hydrogen may also be present in solid solution in nonferrous metals or in surface oxides and in organic lubricating compounds from wire drawing and stamping operations.

Oxygen is intentionally added to argon in the gas metal arc welding (GMAW) of steel to stabilize the arc. Oxygen can also be drawn in from the atmosphere or result from the dissociation of water vapor, carbon dioxide, or a metal oxide. Welding-grade argon and helium are high-purity gases. Thus, they are rarely the source of reactive gases in gas tungsten arc welding (GTAW) and gas metal arc welding. Other processes, such as submerged arc welding or electron beam welding (EBW), use a liquid slag or a vacuum to prevent reactions with atmospheric gases. Nitrogen is picked up from the atmosphere. It is normally not intentionally used as a shielding gas. Nitrogen is sometimes used as a purge gas.

In the welding of steels, gas-metal reactions occur in several steps. First, the diatomic gas molecules are broken down in the high temperature of the welding atmosphere. Then, the gas atoms dissolve in the liquid metal. Reaction rates are extremely fast at temperatures of 3000°F (1650°C) and higher. Once dissolved in the steel, oxygen and nitrogen generally react with intentionally added deoxidizers such as manganese, silicon, and aluminum. These oxides form a slag and float to the surface of the weld or precipitate in the metal as discrete oxides. Oxygen contents of 250 to 600 parts per million (ppm) are not uncommon in steels joined by consumable-electrode arc welding processes. Oxides and nitrides are present as small discrete particles. Although they reduce the ductility and notch toughness of steel weld metal, the resulting mechanical properties are satisfactory for most commercial applications.

In consumable electrode welding, the oxide content of steel weld metal is significantly greater than the nitrogen content. This is the case because oxygen is intentionally present in arc atmospheres, whereas nitrogen is not. If the weld metal does not contain sufficient deoxidizers, the soluble oxygen will react with soluble carbon to produce carbon monoxide (CO) or carbon dioxide (CO_2) during solidification. The gas molecules will be rejected during solidification and produce porosity and less alloying in the weld metal.

Hydrogen is always present in the arc atmosphere if only in small quantities. Hydrogen atoms are soluble in liquid steel and less soluble in solid steel. Excess hydrogen that is rejected during solidification will cause porosity. A more significant problem is created by the hydrogen that remains dissolved in the solid steel. When it is present in significant amounts, delayed cracking can occur, as described in the section titled "Solid-State Reactions."

In the welding of nonferrous metals, the primary gas-metal reactions of concern involve the solution, reaction, and evolution of hydrogen or water vapor. These gases should therefore be excluded from the molten weld pool. When welding aluminum or magnesium and their alloys, hydrogen is often introduced into the weld pool from hydrated oxides on the surfaces of the filler wire or workpieces, or both. It is rejected from the metal during solidification to produce porosity. For this reason, aluminum and magnesium filler metals should be stored after cleaning in sealed, desiccated containers. Mechanical cleaning or vacuum heating at 300°F (150°C) is recommended for workpieces or filler metals that have been exposed to moist air. As the hydrogen solubility difference between the liquid and solid states for magnesium is less than that for aluminum, the tendency for hydrogen-produced porosity is lower in this metal.

6. See the discussion of solidification rates in Chapter 3 of this volume.

In the case of copper and copper alloys, hydrogen reacts with any oxygen present in the molten weld pool during solidification, producing water vapor and thus porosity. The filler metals for copper alloys contain deoxidizers to prevent this reaction. Porosity caused by water vapor does not form in alloys of zinc, aluminum, or beryllium because these elements form stable oxides. However, porosity from water vapor can form in nickel-copper and nickel alloy weld metal. Therefore, filler metals for these alloys generally contain strong deoxidizers.

Titanium alloys are embrittled by reaction with a number of gases, including nitrogen, hydrogen, and oxygen. Consequently, these elements should be excluded from the arc atmosphere. Welding should be performed under carefully designed inert gas shielding or in vacuum. Titanium heat-affected zones are also significantly embrittled by reaction with oxygen and nitrogen. Titanium weldments should be shielded so that any surface heated to over 500°F (260°C) is completely protected by an inert gas. The surface appearance of the titanium weld zone can indicate the effectiveness of the shielding. A light bronze color indicates a small amount of contamination, a shiny blue color indicates more contamination, and a white flaky oxide layer indicates excessive contamination.

Hydrogen is the major cause of porosity in titanium welds. The hydrogen source, as in other nonferrous and ferrous metals, can be the surface of the filler metal. In addition, soluble hydrogen in the filler metal and the base metal can contribute significantly to the total hydrogen in the molten weld pool.

Liquid-Metal Reactions. During the welding process, nonmetallic liquid phases that interact with the molten weld metal are frequently produced. These liquid phases are usually slags formed by the melting of an intentionally added flux.

Slags produced in the shielded metal arc, submerged arc, and electroslag welding processes are designed to absorb deoxidation products and other contaminants produced in the arc and molten weld metal. The quantity and type of nonmetallic deoxidation products generated during the arc welding of steel are directly related to the specific shielding and deoxidants used. These products—primarily silicates of aluminum, manganese, and iron—generally float to the surface of the molten weld pool and become incorporated in the slag. However, some can become trapped in the weld metal as inclusions. The cleanliness of the weld metal is influenced by the quantity of nonmetallic products produced and the extent to which they can be removed with the slag. Clearly, the more strongly oxidizing the arc environment is, the more deoxidation is required, and the greater the quantity of nonmetallic products is produced.

Another important effect that results from the interaction of the liquid and solid state is the weld discontinuity referred to as *hot cracking*. This phenomenon arises during the solidification of the weld metal whenever the interdendritic liquid (i.e., the last region to freeze) has a substantially lower freezing temperature than the previously solidified metal. Under these conditions, shrinkage stresses produced during solidification become concentrated in the small liquid region, producing microcracks between the dendrites. The term "hot cracking" is used because these cracks occur at temperatures close to the solidification temperature. They are promoted by any compositional variations produced by segregation in the weld metal that produce a low-melting interdendritic liquid.

The most common cause of hot cracking in welds is the presence of low-melting-point phases that wet the dendrite surfaces. This may result from the presence of sulfur, lead, phosphorus, and other elements in the metal that depress the melting point. In some ferrous alloys such as stainless steels, silicates have been found to produce cracking.

The control of cracking in ferrous alloys is usually accomplished by controlling the amount and type of sulfides that form as well as the amount and type of minor alloy constituents that may promote cracking. In carbon and low-alloy steel welds, manganese-to-sulfur composition ratios of 30 or more are used to prevent hot cracking in weld metal. In austenitic stainless steel weld metal, a duplex microstructure (e.g., austenite combined with delta ferrite) effectively prevents cracking. For this reason, austenitic stainless steel filler metals are formulated so that the weld metal will contain 2% to 8% ferrite at room temperature. In greater amounts, ferrite may adversely affect the properties of the weld metal.

Solid-State Reactions. With respect to the behavior of weld metals, a number of solid-state reactions function as strengthening mechanisms in the weld metal. These are discussed in detail later in this chapter. In terms of the interactions that occur during the welding process, however, some important phenomena involving solid-state transformations and subsequent reactions with dissolved gases in the metal exist. The most significant of these, often referred to as *delayed cracking,* involves the formation of cold cracks in steel weld metal or heat-affected zones. The steels most susceptible to this type of cracking are those that transform to martensite during the cooling portion of the weld thermal cycle.

Delayed cracking occurs after the weld has cooled to ambient temperature, which may sometimes be hours or even days after welding. It results when dissolved hydrogen remains in the weld metal during solidification and subsequent transformation to martensite. Because delayed cracking is always associated with dissolved hydrogen, two precautions are applied universally to minimize the risk of its occurrence. First, the base metal is preheated to slow the cooling rate. The use of preheat prevents the formation of a crack-susceptible microstructure and promotes the escape of hydrogen from the steel by diffusion. In addition, low-hydrogen welding processes and practices are employed.

Hydrogen is relatively soluble in austenite and virtually insoluble in ferrite. Upon rapid cooling, the austenite transforms into either an aggregate of ferrite and carbide or into martensite, and hydrogen is trapped in solution. In a plain carbon steel, this transformation takes place at a relatively high temperature (near 1300°F [700°C]) even if cooling is rapid. Consequently, the hydrogen atoms have sufficient mobility to diffuse out of the metal. Moreover, the high-temperature transformation product (i.e., ferrite plus carbide) that forms in the weld metal and heat-affected zone is relatively ductile and crack resistant. A rapidly cooled hardenable steel transforms at a much lower temperature. Therefore, the hydrogen atoms have lower mobility, and the microstructure is martensitic and more crack sensitive. This combination is more likely to cause cracking.

The association of hydrogen with delayed cracking led to the development of low-hydrogen covered electrodes. Low-hydrogen electrode coverings must be kept as free of moisture as possible as water is a potent source of hydrogen. To prevent moisture contamination, the electrodes are frequently supplied in hermetically sealed containers. Once exposed to air, these electrodes should be stored in a desiccated environment or at a temperature of approximately 200°F to 500°F (100°C to 250°C). Electrodes that have become hydrated by exposure to the atmosphere must be rebaked (i.e., dried) using the procedures recommended by the manufacturer.

Another solid-state reaction that affects the mechanical properties of the weld joint in ferrous and nonferrous alloys is the precipitation of second phases during cooling. The precipitation of a second phase is particularly deleterious in grain boundaries because the grain boundaries are continuous throughout the metal. A concentration of a second phase at grain boundaries may significantly reduce ductility and toughness.

Strengthening Mechanisms in Weld Metals. Fewer practical methods exist for the metal strengthening of weld metals as compared to base metals. Weld metals are usually not cold-worked, for example. However, four mechanisms are used to strengthen weld metals, and, when applicable, their effects are additive. These four methods are solidification grain structure, solid-solution strengthening, transformation hardening, and precipitation hardening. The first mechanism is common to all welds, while the second is applicable to any alloy type. Transformation and precipitation hardening apply only to specific groups of alloys.

Solidification Grain Structure. As mentioned previously, the rapid freezing of the weld metal creates a segregation pattern within each grain. The resulting microstructure consists of fine dendrite arms in a solute-rich network, as shown in Figure 4.24. This type of microstructure impedes plastic flow during tensile testing. As a result, the ratios of yield strength to tensile strength are typically higher for weld metals than for base metals.

Solid-Solution Strengthening. Weld metals are strengthened by the addition of alloys. Both substitutional and interstitial alloying elements strengthen ferrous and nonferrous weld metals. This process is shown schematically in Figure 4.1 and illustrated in Figure 4.3.

Transformation Hardening. Transformation hardening can take place in ferrous weld metals even if the austenite decomposition product is not martensite. The rapid cooling rates achieved during the cooling portion of weld thermal cycles decrease the temperature of the austenite transformation. The ferrite-carbide aggregate formed at low transformation temperatures is fine and stronger than that formed at higher transformation temperatures. The effect of the transformation temperature on the ultimate tensile strength of steel weld metal is shown in Figure 4.27.

Precipitation Hardening. Weld metals of precipitation-hardening alloy systems can often be strengthened by an aging process. In most commercial applications, the precipitation-hardened weldments are aged after welding without the benefit of a solution heat treatment. In multipass welds, some zones of weld metal are aged or overaged by the welding heat.

The heat-affected zone also contains overaged metal. In spite of the presence of some overaged metal, an aging heat treatment strengthens the weld metal and the heat-affected zone. However, these may not strengthen to the same degree as the base metal does because of the presence of the overaged metal. Some precipitation-hardening weld metals of aluminum age naturally at room temperature.

Heat-Affected Zone

In theory, the heat-affected zone includes all regions heated to any temperature above the ambient. From a practical point of view, however, it comprises only those regions that are measurably influenced by the heat of the welding process. Thus, for a plain carbon as-rolled steel, the heat-affected zone may not include regions of the base metal heated to less than approximately

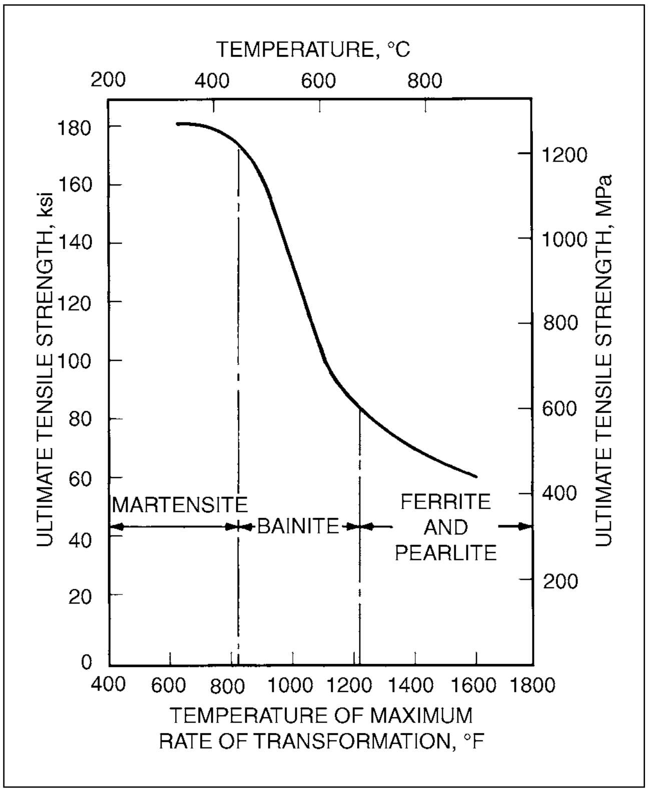
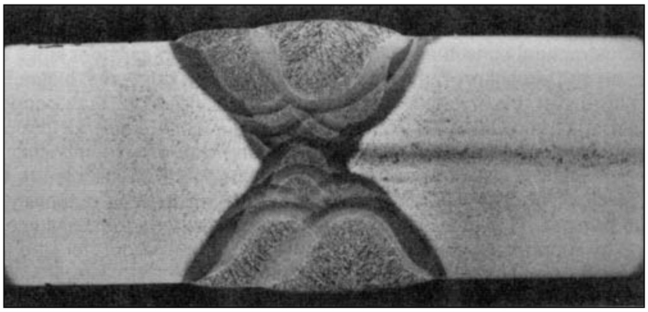


Figure 4.27—Effect of Transformation Temperature on the Strength of Steel Weld Metal



Source: Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 9.46.

Figure 4.28—Macrosection of a Carbon-Manganese Steel Weld Approximately 1-1/2 in. (40 mm) Thick, Showing Positions of Individual Weld Beads and Their Overlapping Heat-Affected Areas

1350°F (700°C) since the welding heat has little influence on those regions. In contrast, in a heat-treated steel that has been quenched to martensite and tempered at 600°F (315°C), any area heated above 600°F (315°C) during welding would be considered part of the heat-affected zone, as quenching and tempering changes the mechanical properties of the metal. To cite an extreme example, in a heat-treated aluminum alloy age-hardened at 250°F (120°C), any portion of the welded joint heated above this temperature would be part of the heat-affected zone.

Heat-affected zones are often defined by a variation in hardness or changes in microstructure in the vicinity of the welded joint. These changes in microstructure produced by the welding heat can be observed by etching or measured in hardness profiles. It should be noted, however, that in many cases these are arbitrary measures of the heat-affected zone, though they may be of practical value in the testing and evaluation of welded joints.

A cross section of a multipass weld in a carbon-manganese steel plate is presented in Figure 4.28. It can be observed that each weld pass possesses a peripheral area that was visibly affected when the bead was deposited. These overlapping heat-affected areas at the fusion faces extend through the full thickness of the plate. In a multipass weld, it is common for the deposited weld metal to be affected by the heat of subsequent welding. However, this deposited weld metal is not considered part of the heat-affected zone.

Strength and toughness in the heat-affected zone of a welded joint depend upon the type of base metal, the welding process, and the welding procedure. The base metals that are most influenced by welding are those strengthened or annealed by heat treatments inasmuch as a weld thermal cycle involves high temperatures. The temperatures in the weld heat-affected zone vary from ambient to near the liquidus temperature. Metallurgical processes that proceed slowly at lower temperatures can proceed rapidly to completion at temperatures close to the liquidus.

To understand the various effects of welding heat on the heat-affected zone, it is best to consider these effects in terms of four different types of alloys that may be welded:

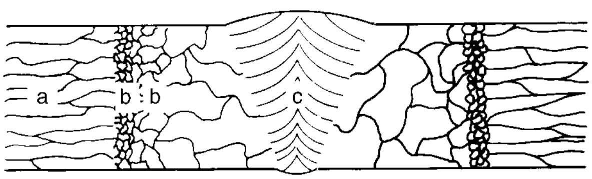
1. Alloys strengthened by solid solution,
2. Alloys strengthened by cold work,
3. Alloys strengthened by precipitation hardening, and
4. Alloys strengthened by transformation (martensite).

Some alloys can be strengthened by more than one of the processes listed above. Nonetheless, for purposes of simplicity, these processes are described separately.

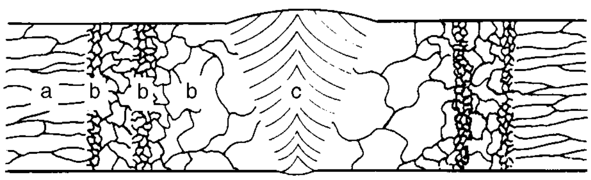
Solid-Solution-Strengthened Alloys. Solid-solution-strengthened alloys exhibit the fewest problems with respect to the weld heat-affected zone. If they do not undergo a solid-state transformation, the effect of the thermal cycle is small, and the properties of the heat-affected zone are largely unaffected by welding.

Grain growth occurs next to the weld interface as a result of the high peak temperature. This does not significantly affect the mechanical properties if the grain-coarsened zone is only a few grains wide. Commonly used alloys strengthened by solid solution are aluminum and copper alloys as well as hot-rolled low-carbon steels. Ferritic and austenitic stainless steels also belong to this category.

Strain-Hardened Base Metals. Strain-hardened base metals recrystallize when heated above the recrystallization temperature. The heat of welding recrystallizes the heat-affected zones in cold-worked metals and softens the metal considerably. The weld cross sections shown in Figure 4.29 illustrate the effect of the weld thermal cycles on cold-worked microstructures. The unaffected base metal, labeled "a" in Figure 4.29(A), exhibits the typical elongated grains that result from mechanical deformation. Fine, equiaxed grains have formed in the areas labeled "b," where the temperature of the heat-affected-zone exceeded that of recrystallization, and grain growth has taken place at higher temperatures near the fusion zone. The resulting recrystallized heat-affected zone is softer and weaker than the cold-worked base metal, and the strength cannot be recovered by heat treatment.



(A) No Phase Change When Heated



(B) Allotropic Transformation When Heated

Figure 4.29—Recrystallization of Cold-Worked Grains in the Heat-Affected Zone

If the cold-worked materials undergo an allotropic transformation when heated, the effects of welding are even more complex. Steel, titanium, and other alloys that exhibit allotropic transformations may have two recrystallized zones, as illustrated in Figure 4.29(B). The first fine-grained zone results from the recrystallization of the cold-worked alpha phase. The second fine-grained zone results from the allotropic transformation to the high temperature phase.

Precipitation-Hardened Alloys. Alloys strengthened by precipitation hardening respond to the heat of welding in the same manner as work-hardened alloys, that is, the heat-affected zone undergoes an annealing cycle. The response of the heat-affected zone is more complex because the welding thermal cycle produces different effects in different regions. The heat-treating sequence for precipitation hardening consists of solution treating, quenching, and aging. The welding heat resolution treats the heat-affected-zone regions closest to the weld and produces a relatively soft, single-phase solid solution with some coarse grains. This region can be hardened by a postweld aging treatment.

Those regions of the heat-affected zone that are heated to temperatures below the solution treatment temperature are overaged by the welding heat. A postweld aging treatment will not reharden this region. If the welding heat does not raise the temperature of the heat-affected zone above the original aging temperature, the mechanical properties are not significantly affected. The heat-affected-zone structure of a precipitation-hardened alloy is illustrated in Figure 4.30.

It is difficult to weld high-strength precipitation-hardenable alloys without some loss of strength, but three techniques are used to minimize the loss. One method involves resolution treating, quenching, and aging the weldment. Although this is the most effective technique, it is also expensive and may be impractical in some cases.

A second approach involves welding precipitation-hardened base metal and subsequently reaging the weldment. This treatment raises the strength of the solution-treated region of the heat-affected zone, but it causes no improvement in the strength of the overaged zone. The other technique used to minimize the loss of strength is to weld the base metal in the solution-treated condition and age the completed weldment. The overaged zone is still the weakest link, but the overall effect is an improvement over the previous approaches.

Since the weld thermal cycle lowers the strength of the heat-treated base metal, welding processes utilizing

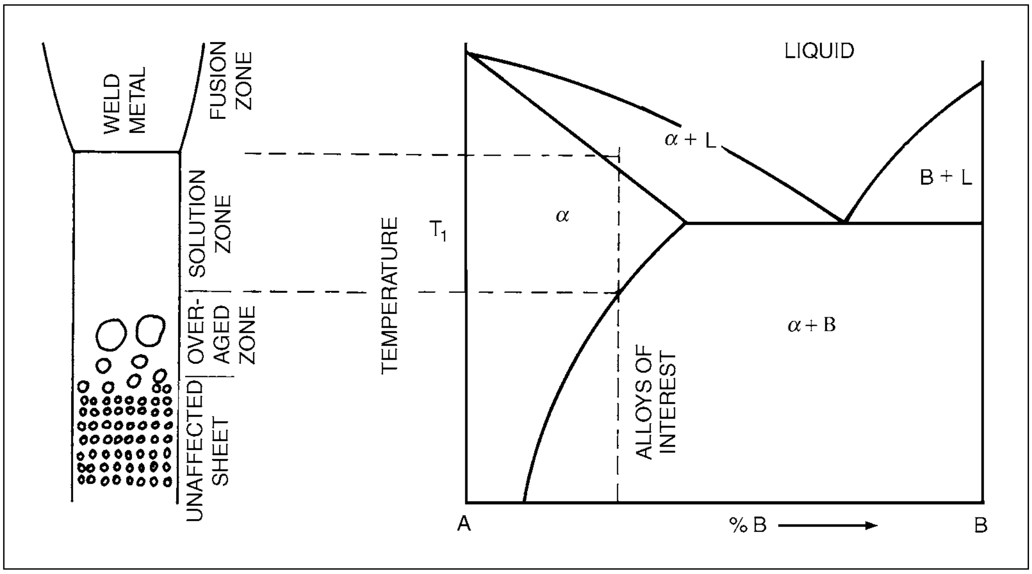


Figure 4.30—Growth of Precipitates in the Heat-Affected Zone of Precipitation-Hardened Alloy

high heat input are not recommended for these alloys. Low heat input minimizes the width of the heat-affected zone and the amount of softened base metal.

Transformation-Hardening Alloys. The transformation-hardening alloys of interest are the steels with sufficient carbon and alloy content to transform to martensite upon cooling from welding. These are steels that have been heat treated to tempered martensite prior to welding or that have adequate hardenability to transform to martensite during a weld thermal cycle. In either case, the heat-affected zone is affected by the weld thermal cycle in approximately the same manner. The heat-affected zones of a transformation-hardening alloy together with the iron-carbon phase diagram are illustrated in Figure 4.31.

The grain-coarsened region is located near the weld interface in Region 1. Rapid austenitic grain growth occurs in this region when the region is exposed to temperatures near the melting point. The large grain size increases hardenability, and this region can readily transform to martensite on cooling.

Region 2 is austenitized, but the temperature is too low to promote grain growth. The hardenability of Region 2 is not significantly increased by grain growth, but this region may transform to martensite if the cooling rate is sufficiently rapid or the alloy content is great enough. In Region 3, some grains transform to austenite, while others do not. The austenite grains are very fine. No austenitic transformation takes place in Region 4, but the ferrite grains may be tempered by the heat of welding.

The width of the heat-affected zone and the widths of each region in the heat-affected zone are controlled by the welding heat input. High heat inputs result in slow cooling rates. Therefore, the heat input determines the final transformation products.

High-carbon martensite is hard and strong, and it can create problems in the heat-affected zone. The hardness of a weld heat-affected zone is a function of the carbon content of the base metal. With increasing carbon content, toughness in the heat-affected zone decreases while hardness and crack susceptibility increase. High-carbon martensite alone does not cause cracking; dissolved hydrogen and residual stresses are also necessary. The same precautions used to prevent delayed cracking in weld metal (see above) also prevent cracking in the heat-affected zone.

The hardness of a weld heat-affected zone is usually a good indication of the amount of martensite present and the potential for cracking. Although cracking rarely occurs when Brinell hardness is below 250 HB, it is common when hardness approaches 450 HB and no precautions are taken.

Figure 4.32 presents the microstructure and microhardness of three weld beads deposited under different conditions of preheat and postheat on 0.25% carbon steel. The heat-affected-zone Knoop hardness of the

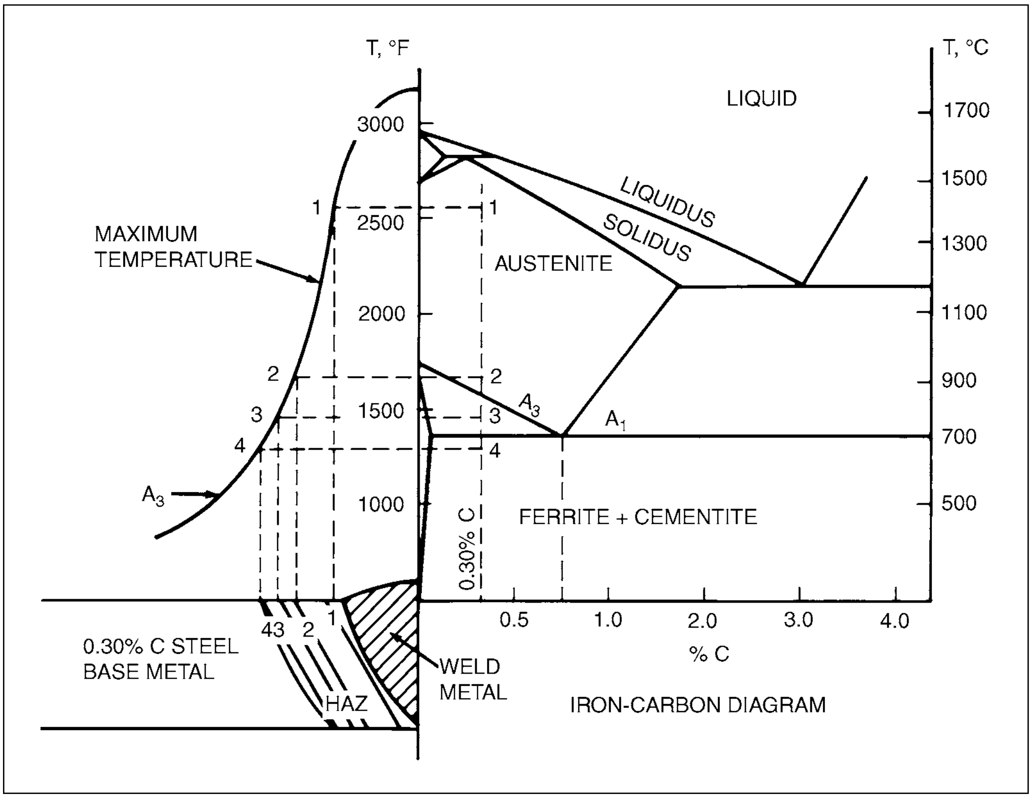


Figure 4.31—Approximate Relationships Between the Peak Temperature, the Distance from Weld Interface, and the Iron-Carbon Phase Diagram

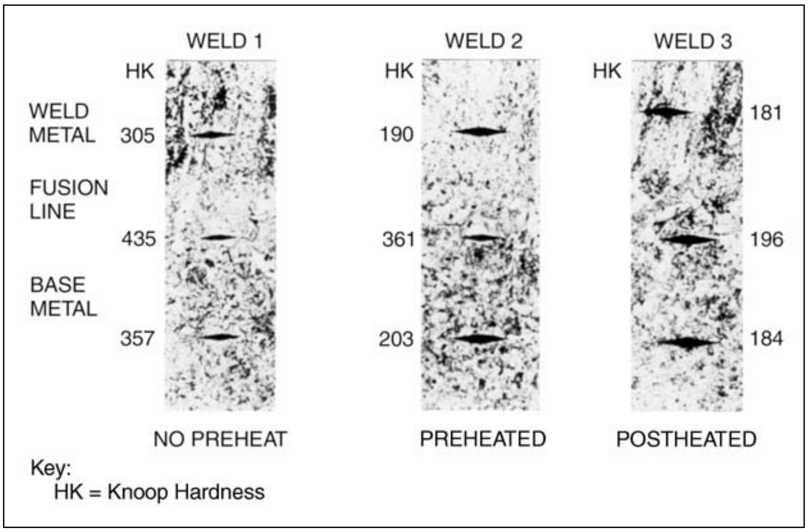


Figure 4.32—Hardness of the Base Metal, Heat-Affected Zone, and Weld Metal of 0.25% Carbon Steel, 100X Magnification

weld produced without the preheat was 435 HK. The second weld bead was deposited on a preheated plate, and the heat-affected-zone Knoop hardness was 361 HK. The third plate was tempered after welding at 1100°F (595°C), and the heat-affected-zone hardness was 196 HK. The hardness of heat-affected zone of the second and third weld beads was markedly lower than that of the first weld. This suggests that a postweld heat treatment may be required to reduce the hardness of the weld metal and the heat-affected zone in hardenable steels.

Special precautions may be necessary when welding hardenable steels that have been intentionally heat-treated to produce a tempered martensitic microstructure. It is usually desirable to use a low welding heat input to control the size of the heat-affected zone and a high preheat temperature to control the cooling rate of the weld. The welding recommendations of the steel manufacturer should be followed in preparing welding procedures for low-alloy, high-strength steels.

Base Metal

The third component in a welded joint is the base metal. The base metal is selected by the designer for the specific application based on a specific property or combination of properties, such as yield or tensile strength, notch toughness, corrosion resistance, or density. Many common engineering alloys are readily weldable. However, some alloys are more difficult to weld and require special precautions.

The term *weldability* refers to the capacity of a material to be welded under the imposed fabrication conditions into a specific suitably designed structure and to perform satisfactorily in the intended service.[7] According to this definition, the weldability of some systems may be poor under some conditions but satisfactory under other conditions. One example is ASTM A 514 steel, a heat-treated 100 ksi (689 MPa) yield strength constructional alloy. All grades of this material have satisfactory weldability, provided the base metal is sufficiently preheated, low-hydrogen welding procedures are followed, and the allowable heat input limitations are not exceeded.

Weldability is affected by section shape and thickness, cleanliness of the surfaces to be joined, and the mechanical properties of the metals. However, the primary factor affecting the weldability of a base metal is its chemical composition. For each type of metal, there are welding procedural limits within which sound weldments with satisfactory properties can be fabricated. If these limits are wide, the metal is said to have good weldability. If the limits are narrow, the metal is said to have poor weldability. If extraordinary precautions are necessary, the material is often termed *unweldable*. In some cases and in certain industries, however, unweldable materials are routinely welded under tight controls with vigorous inspection procedures and acceptance criteria. These methods are followed because welding may be the only (or at least the best) method to achieve the desired function within the design criteria for the whole assembly. The weldability of several types of commercial alloys is discussed in the following section.

WELDABILITY OF COMMERCIAL ALLOYS

The joining procedures implemented for commercial alloys must reflect any special metallurgical aspect of the operation. For instance, the presence of a coarse grain structure (ASTM Number 5 or coarser) in the base material can restrict the use of processes having high energy density deposition, such as electron beam welding and high-current and heat-input spray transfer gas metal arc welding. Metallurgical factors can have a controlling influence on procedures for the welding of dissimilar materials and precipitation-hardenable alloys. Any welded joint can undergo metallurgical changes when subjected to cold work and heat treatment. For high-temperature service, both metallurgical and design considerations are important in order to obtain optimum life in fabricated equipment.

The metallurgical considerations involved in assessing the weldability of commercial alloys are especially complex when dissimilar alloys are to be joined. The composition of the weld deposit is controlled not only by the electrode or filler metal but also by the amount of dilution from the two base metals. Many combinations of dissimilar metals are possible, and the degree of dilution varies with the welding process, the operator technique, and the joint design. All these factors influence the selection of a joining method and welding material to produce a welded joint having the properties required by the application.

In many cases, more than one welding product satisfies the requirement of metallurgical compatibility. In this case, the selection of a product is based on the strength required, the service environment to be withstood, or on economics (i.e., cost of the welding product). In addition to the dilution of the weld metal, other factors such as differences in thermal expansion and melting point often influence the selection of filler metal for dissimilar joints, especially if the joints are to be exposed to high service temperatures.

7. American Welding Society (AWS) Committee on Definitions, 20XX, *Standard Welding Terms and Definitions,* AWS A3.0:20XX, Miami: American Welding Society, p. 66.

Unequal expansion of joint members places stress on the joint area and can cause a reduction in fatigue strength. If one of the base metals is of lower strength, a filler metal that has an expansion rate near that of the weaker base metal should be selected. The stress resulting from unequal expansion is then concentrated on the stronger side of the joint.

A joint between austenitic stainless steel and mild steel illustrates the importance of thermal expansion considerations. The expansion rate of mild steel is lower than that of stainless steel. From the standpoint of dilution, either a stainless-steel electrode or a nickel-chromium-iron (Ni-Cr-Fe) welding product would be suitable. The stainless-steel electrode has an expansion rate near that of the stainless-steel base metal, and Ni-Cr-Fe welding products have expansion rates near that of mild steel. If the joint is welded with the stainless-steel electrode, both the weld metal and the stainless base metal will expand more than the mild steel, placing the line of differential expansion along the weaker (mild-steel) side of the joint. If the joint is welded with a Ni-Cr-Fe welding product, the stress resulting from unequal expansion is confined along the stronger, stainless-steel side of the joint.

During welding, differences in melting point between the two base metals or between the weld metal and base metal can result in the rupture of the material having the lower melting point. The solidification and contraction of the material with the higher melting point place stress on the material with the lower melting point, which is in a weak, incompletely solidified condition. The problem can often be eliminated by the application of a layer of weld metal on the base metal with the low melting point before the joint is welded. A lower stress level is present during the application of this weld-metal layer.[8] During completion of the joint, the previously applied weld metal serves to reduce the melting point differential across the joint.

Several of the alloys used commercially in welded products are described briefly below.[9]

STEELS

Most commercial steels can be classified as plain carbon, low-alloy, or high-alloy steels. Steels specifically designed for structural, pipeline, and pressure vessel applications have chemical compositions that have been tailored for weldability. Controlling the preheat, hydrogen content, and heat input reduces or eliminates undesirable transformation products (such as martensite) that can be detrimental to the integrity of the weldment. The governing codes and procedures for structures, pipelines, and pressure vessels are written to ensure that variables such as the selection of filler metal, section thickness, preheat, and heat input consistently produce a weldment that is sufficiently sound, strong, ductile for the intended service.

One example of a specially designed steel is ASTM A 216, Grade WCB, which is used for pressure vessel service and valve and pump castings. Its ability to be welded and weld-repaired by foundries, equipment manufacturers, or in service makes it a popular selection. Higher-strength structural steels (such as A 214) may require low-hydrogen practice and greater control of preheat and heat input, but they are still considered weldable.

An understanding of welding metallurgy becomes critical in the use of heat-treatable alloy steels such as AISI-SAE 4140 or AISI-SAE 4340 for machinery applications. As these steels are designed to achieve high strength through heat treatment, weldability is not a consideration. As they have high carbon equivalents, they are difficult to weld and require special fabrication considerations.

When welding a steel component or structure, it is important to select a grade that has good weldability and meets the mechanical requirements of the design. When the alloyed steels are used for their mechanical properties as a primary consideration, weldability becomes more difficult. The principles of welding metallurgy are best applied in these situations to ensure that the final weldment is strong, ductile, and free of discontinuities.

The typical mechanical properties of some commercial steel grades are shown in Table 4.2. Plain carbon, low-alloy, and high-alloy steels are discussed in more detail below.

Plain Carbon Steels

Plain carbon steel consists of iron with less than 1.0% carbon and minor amounts of manganese, phosphorus, sulfur, and silicon. The properties and weldability of this steel depends mainly on its carbon content, although other alloying and residual elements influence properties to a limited extent. Plain carbon steels are frequently categorized as low-, medium-, and high-carbon steels.[10] Weldability is excellent for low-carbon steels, good to fair for medium-carbon steels, and poor for high-carbon steels.

8. INCO Alloys International, 1989, *Welding,* Huntington, West Virginia: INCO Alloys International, pp. 23–31.

9. For a complete discussion of metals and their weldability, see Oates, W. R., ed., 1996, *Materials and Applications—Part 1*, Vol. 3 of the *Welding Handbook,* 8th ed., and Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of the *Welding Handbook,* 8th ed., Miami: American Welding Society.

10. The American Welding Society (AWS) publishes specifications for carbon steel filler metals for use with the arc welding processes.

Table 4.2
Typical Mechanical Properties of Some Commercial Steels at Room Temperature

Material	Type	Conditions	Ultimate Tensile Strength ksi (MPa)	Yield Strength 0.2% Offset ksi (MPa)	Elongation in 2 in. (50 mm), %	Hardness Brinell	Hardness Rockwell
Mild steel	Plain carbon	Hot-rolled	55 (379)	30 (207)	30	110	62B
A36	Plain carbon	Hot-rolled	65 (448)	38 (262)	28	135	74B
A285	Plain carbon	Hot-rolled	70 (483)	39 (266)	27	140	77B
Medium carbon steel	Plain carbon	Oil-quenched and tempered at 400°F (204°C)	120 (827)	93 (641)	18	242	100B
		Oil-quenched and tempered at 1200°F (649°C)	80 (552)	62 (427)	30	202	(23C) 90B
A514	Low-alloy	Water-quenched and tempered	115 (793)	95 (655)	18	230	98B (21C)
A240 Type 304	Stainless steel	Annealed	90 (621)	40 (276)	60	160	83B
A216 Grade WCB	Casting	Normalized and tempered	70 (483)	36 (248)	22	180	89B

Alloy Steels

The carbon content of alloy steels intended for welded applications is typically less than 0.25% and frequently below 0.15%. Other alloying elements such as nickel, chromium, molybdenum, manganese, and silicon are added to increase the strength of these steels at room temperatures as well as to impart better notch toughness at low temperatures. These elements also alter the response of the steels to heat treatment and can improve their corrosion resistance. Alloy additions adversely affect the crack susceptibility of alloy steels. Therefore, low-hydrogen welding processes should be used on these steels. Preheat may also be required.

Modern design often utilizes steels that have higher strength and toughness than the plain carbon and structural steels. A yield strength of 50,000 pounds per square inch (psi) (345 megapascal [MPa]) and a tensile strength of 70,000 psi (480 MPa) are achieved in the as-rolled condition by adding two or more alloying elements. Adequate weldability is maintained by restricting the carbon content to a maximum of 0.20%. Some of these steels are heat treated up to 100,000 psi (690 MPa) yield strength, and they have better notch toughness than ordinary carbon steel. The selection of the proper filler metal and welding procedures will result in comparable properties in welded joints in these steels.[11]

A variety of steels have been developed for use in machinery parts. These steels are classified according to chemical composition by the AISI-SAE classification system. The weldability of these steels depends on their chemical composition. The more they are alloyed, the farther the nose of the CCT diagram is moved to the right.

Other steels have been developed to meet the needs of the cryogenic industry. Those steels have good notch toughness at temperatures well below 0°F (–18°C). Fine-grained aluminum-killed steels with up to 10% nickel are frequently used for cryogenic service.

Alloy steels have also been developed for high-temperature service in welded structures such as steam boilers, oil refining towers, and chemical-processing retorts. Additions of chromium and molybdenum give these steels structural stability and provide high creep and stress-rupture values at temperatures up to 1100°F (595°C).

Stainless Steels. Stainless steels are important commercial alloy steels. They contain at least 12% chromium, and many of the grades have substantial amounts of nickel. Other alloying elements are added for special purposes. Stainless steels are noted for their resistance to attack by many corrosive media at atmospheric or elevated temperatures. The four basic types of stainless steel are austenitic, ferritic, martensitic, and duplex. Some are precipitation-hardenable steels.

Austenitic stainless steels are produced by adding alloying elements that stabilize austenite at room temperature. Nickel is the most important austenite-stabilizing element. Manganese, carbon, and nitrogen also stabilize austenite. Chromium, nickel, molybdenum, nitrogen, titanium, and niobium provide the

11. The American Welding Society publishes low-alloy-steel filler metal specifications for the common arc welding processes.

austenitic stainless steels with special properties of corrosion resistance, oxidation resistance, and elevated temperature strength. Carbon can contribute to elevated temperature strength, but it may reduce corrosion resistance by forming a chemical compound with chromium. As the austenitic alloys cannot be hardened by heat treatment, they do not harden in the weld heat-affected zone. The austenitic stainless steels have excellent weldability.

Ferritic stainless steels contain from 12% to 27% chromium with small amounts of austenite-forming elements. As the ferrite phase is stable up to the melting temperature, no undesirable martensite is formed. However, slow cooling through the temperature range circa 885°F (474°C) should be avoided, as this precipitates a brittle phase.

Martensitic stainless steels contain the smallest amount of chromium and exhibit high hardenability. The cutlery grades are martensitic stainless steels. As the martensitic heat-affected zone is susceptible to cracking, care must be taken when welding these steels. Preheating and postheating treatments are necessary to prevent cracking.

Duplex stainless steels are chosen for their improved corrosion resistance. They form no martensitic transformation product from welding. Some of the duplex alloys have limited weldability due to the undesirable formation of a sigma (σ) phase upon cooling.

Most stainless steels are readily joined by arc, electron beam, laser beam, resistance, and friction welding processes. Gas metal arc, gas tungsten arc, flux cored arc, and shielded metal arc welding are commonly used. Plasma arc and submerged arc welding are also suitable methods. Oxyacetylene welding is seldom recommended, and its use for sections thicker than 0.13 in. (3.3 mm) is discouraged.

Other Alloy Steels. Other alloy steels have been specially designed for applications that require outstanding mechanical properties or strength and ductility at elevated temperatures. These steels range from chromium-molybdenum steels (ASTM A387) and nickel steels (ASTM A353 and A553) to nickel-cobalt maraging steels and tool steels. Important compositions are discussed in *Materials and Applications—Part 2*, Volume 4 of the *Welding Handbook*, 8th edition.[12]

In tool steels, alloys are added to extend the time required for transformation. It follows that they become proportionately more difficult to weld. Although the chromium-molybdenum and nickel steels are typically welded under controlled conditions, these tool steels may be fabricated and repaired using any of the common arc welding processes (e.g., gas tungsten arc welding, gas metal arc welding, shielded metal arc welding, and submerged arc welding). Dies, punches, and shears are made from high-carbon tool steels that contain moderate amounts of other alloying elements. Premium quality high-strength alloys may require the use of gas tungsten arc or plasma arc welding to achieve clean weld deposits with suitable mechanical properties.

ALUMINUM ALLOYS

Aluminum and aluminum alloys have a face-centered-cubic crystal lattice structure at all temperatures up to their melting points. The alloys have low density—about one-third that of steel or copper—and excellent corrosion resistance. Aluminum resists corrosion by air, water, oils, and many chemicals because it rapidly forms a tenacious, refractory oxide film on a clean surface in air. As this oxide is virtually insoluble in the molten aluminum, it inhibits wetting by molten filler metals.

Aluminum conducts thermal and electrical energy approximately four times faster than steel. As a result, thick sections may need preheating. In addition, fusion welding requires high heat input, and resistance spot welds require a higher current and a shorter weld time than steel welds of equivalent thickness. As this metal is nonmagnetic, arc blow causes no difficulty. Aluminum is highly reflective of radiant energy and does not change color prior to melting, which occurs at approximately 1200°F (650°C).

Aluminum is strengthened by alloying, cold working, heat treating, and combinations of these methods. Heating during welding, brazing, or soldering may soften aluminum alloys that were previously strengthened by heat treatment or cold working. This behavior must be considered when designing the component and selecting the joining process and manufacturing procedures.

Aluminum is alloyed principally with copper, magnesium, manganese, silicon, zinc, and lithium. Small additions of chromium, iron, nickel, titanium, and lithium are made to specific alloy systems to obtain desired properties and to refine the grain. Alone or in various combinations, magnesium, manganese, silicon, and iron are used to strengthen aluminum by solid solution or by dispersing intermetallic compounds within the matrix. The addition of silicon also lowers the melting point and increases the fluidity of the melted alloy.

Copper, magnesium, silicon, zinc, and lithium additions produce alloys that are heat treatable. These elements become more soluble with increasing temperature. Such alloys can be strengthened by appropriate thermal treatments, which may be supplemented by cold working. However, the heat treatment and the cold work may be negated by the thermal cycle of a joining operation. Heat treatment

12. Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of *Welding Handbook*, 8th ed., Miami: American Welding Society.

in conjunction with or following the welding or brazing step should be provided to restore optimum mechanical properties.[13]

MAGNESIUM ALLOYS

Magnesium and its alloys have a hexagonal close-packed crystal lattice structure. Compared to aluminum alloys, magnesium alloys can sustain only a limited degree of deformation at room temperature. However, their workability increases rapidly with temperature, and at 400°F to 600°F (200°C to 310°C) they can be worked severely. Forming and straightening operations are generally performed at an elevated temperature. Magnesium is well known for its extreme lightness, machinability, weldability, and the high strength-to-weight ratio of its alloys. On an equal volume basis, it weighs about one-quarter as much as steel and two-thirds as much as aluminum.

Magnesium and magnesium alloys oxidize rapidly at welding and brazing temperatures. The oxide inhibits wetting and flow during welding, brazing, or soldering. Thus, a protective shield of inert gas or flux must be used to prevent oxidation during exposure to elevated temperatures.

Magnesium requires relatively little heat to melt because its melting point, latent heat of fusion, and specific heat per unit volume are all relatively low. On an equal volume basis, the total heat of fusion for magnesium is approximately two-thirds that for aluminum and one-fifth that for steel. The high coefficients of thermal expansion and thermal conductivity tend to cause considerable distortion during welding.

The fixtures used for the welding of magnesium must be more substantial than those utilized to join steel. Fixtures similar to those used in welding aluminum are adequate.[14]

COPPER ALLOYS

Copper and most of its alloys have a face-centered cubic crystal lattice. Most commercial copper alloys are solid solutions (single-phase alloys). Fourteen common alloying elements are added to copper. Copper alloys exhibit no allotropic or crystallographic changes on heating and cooling, but several have limited solubility with two phases stable at room temperature. Some of these multiple-phase alloys can be hardened by means of the precipitation of intermetallic compounds. Two-phase copper alloys harden rapidly during cold working, but they usually have better hot-working and welding characteristics than do solid solutions of the same alloy system. The corrosion resistance of copper alloys is often improved by small additions of iron, silicon, tin, arsenic, and antimony.

The most important age-hardening reactions in copper alloys are obtained with additions of beryllium, boron, chromium, silicon, and zirconium. Care must be taken in welding and heat treating such age-hardenable copper alloys. The proper welding process and filler metal must be used. If the preweld properties are required, the weld should be solution-annealed and aged.

It is also important to note that copper alloy weld metals do not flow well without a high preheat. The high heat conductivity of the base metal removes welding heat rapidly from the deposited bead, making it flow sluggishly. The beads will not blend smoothly with the base metal if preheating is inadequate.[15]

NICKEL-BASED ALLOYS

Nickel and its alloys have a face-centered-cubic crystal structure at all temperatures up to their melting points. This makes most solid-solution-strengthened alloys readily weldable. Specific alloys are noted for

13. For additional information on the welding of aluminum, see Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of Welding Handbook, 8th ed., Miami: American Welding Society, and American Welding Society (AWS) Committee on Filler Metal, *Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods,* ANSI/AWS A5.10, Miami: American Welding Society. In addition, the appendices of the two filler metal specifications, American Welding Society (AWS) Committee for Filler Metals and Allied Materials, *Specification for Aluminum and Aluminum Alloy Electrodes for Shielded Metal Arc Welding,* AWS A5.3/A5.3M, Miami: American Welding Society, and American Welding Society (AWS) Committee on Filler Metal, *Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods,* ANSI/AWS A5.10, Miami: American Welding Society, provide useful information on classifications and applications. See also American Welding Society Committee on Piping and Tubing, *Recommended Practices for Gas Shielded Arc Welding of Aluminum and Aluminum Alloy Pipe,* ANSI/AWS D10.7, Miami: American Welding Society.

14. Magnesium filler metals are discussed in American Welding Society (AWS) Committee on Filler Metal, *Specification for Magnesium Alloy Welding Electrodes and Rods,* ANSI/AWS A5.19, Miami: American Welding Society. In addition, for in-depth discussions of magnesium and magnesium alloys, see Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

15. The welding of copper alloys is discussed extensively in Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of *Welding Handbook,* 8th ed., Miami: American Welding Society. Copper alloy filler metals are specified in American Welding Society (AWS) Committee on Filler Metal, *Specification for Covered Copper and Copper Alloy Arc Welding Electrodes,* ANSI/AWS A5.6, Miami: American Welding Society, and American Welding Society (AWS) Committee on Filler Metal, *Specification for Copper and Copper Alloy Bare Welding Rods and Electrodes,* ANSI/AWS A5.7, Miami: American Welding Society.

their resistance to corrosion and for their high-temperature strength and toughness.

The principal alloying elements added to commercial nickel alloys are copper, chromium, iron, molybdenum, and cobalt. These additives, with the exception of molybdenum, form binary solid solutions with nickel in the commercial alloys and have relatively little effect on weldability. Molybdenum present above 20% forms a second phase with nickel, and the resulting two-phase alloys produced commercially are weldable. Alloying elements added in smaller amounts include aluminum, carbon, magnesium, manganese, niobium, silicon, titanium, tungsten, and vanadium.

High-nickel alloys are strengthened by solid-solution alloying, by dispersion hardening with a metal oxide, and by precipitation-hardening heat treatments. Precipitation hardening is achieved by controlled precipitation in the microstructure of a second phase, essentially the compound nickel aluminum (Ni_3Al). Commercial alloy systems have been developed with nickel-copper, nickel-chromium, nickel-molybdenum, nickel-chromium-molybdenum, and nickel-iron-chromium compositions.

The welding of nickel alloys is similar to the welding of austenitic stainless steels. Arc welding is broadly applicable.[16] Resistance welding is also readily performed, but oxyacetylene welding generally is not recommended. Electron beam welding may achieve greater joint efficiency than gas tungsten arc welding, but heat-affected-zone cracking susceptibility may increase in thick-section welds. Nickel alloys can be brazed with proper base metal preparation, brazing environment, and filler metal selection. Sulfur contaminates nickel-based welds and causes hot cracking. Therefore, the joint and the filler metal must be kept clean.

COBALT ALLOYS

Cobalt has a close-packed-hexagonal crystal lattice up to 750°F (400°C) and a face-centered-cubic crystal lattice above this temperature. Nickel additions to cobalt stabilize the face-centered-cubic structure to below room temperature. Most cobalt alloys contain nickel to retain the inherent ductility of the face-centered-cubic structure. Commercial cobalt-based alloys are widely used in high-temperature applications.

The cobalt alloys commonly welded in fabrication generally contain two or more of the elements nickel, chromium, tungsten, and molybdenum. The latter three form a second phase with cobalt in the commercial alloys. However, the presence of cobalt does not adversely affect weldability.

Other alloying elements such as manganese, niobium, tantalum, silicon, and titanium are not detrimental to welding if kept within specified limits. Elements that are insoluble in cobalt or that undergo eutectic reactions with it—sulfur, lead, phosphorus, and bismuth, for example—may initiate hot cracking in the weld. Therefore, these impurities are maintained at low levels in commercial cobalt alloys.[17]

REACTIVE AND REFRACTORY METALS

The groups of metals known as the reactive and refractory metals include titanium, zirconium, hafnium, niobium (columbium), molybdenum, tantalum, and tungsten. Because these metals oxidize rapidly when heated in air, it is necessary to shield the weld region, including large portions of the heated base metal, from the atmosphere. A high degree of mutual solid solubility exists between all pairs of these metals. Two-component alloys are solid-solution strengthened.

Although the reactive and refractory metals and their alloys can be welded to each other, the ductility may be reduced in some combinations. They cannot be fusion welded directly to alloys of iron, nickel, cobalt, copper, and aluminum because extremely brittle intermetallic compounds are formed in the fusion zone. These welds crack as thermal stresses develop upon cooling.

Titanium Alloys

Pure titanium is a silver-colored metal with a close-packed-hexagonal crystal structure known as the *alpha (α) phase* up to 1625°F (885°C). Above this temperature, the crystal structure of titanium is body-centered-

16. For the filler metal requirements for the shielded metal arc welding of nickel alloys, see American Welding Society (AWS) Committee on Filler Metals, *Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding,* ANSI/AWS A5.11/A5.11, Miami: American Welding Society. For the filler metal requirements for the gas metal arc, gas tungsten arc, plasma arc, and submerged arc welding of nickel alloys, see American Welding Society (AWS) Committee on Filler Metals, *Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods,* ANSI/AWS A5.14/A5.14M, Miami: American Welding Society. The appendices of these filler metal specifications provide a wealth of information on the classification and application of the electrodes. For further discussion of the welding of nickel alloys, see Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

17. Cobalt alloy filler metals are not covered by any American Welding Society specifications. The Society of Automotive Engineers (SAE) publishes material specifications for use by the aerospace industry. Several aerospace material specifications (AMSs) address cobalt welding materials. See, for example, Society of Automotive Engineers (SAE), *Cobalt Alloy, Corrosion and Heat Resistant, Covered Welding Electrodes 51.5 Co 20Cr 10Ni 15W,* SAE AMS 5797C, Warrendale, Pennsylvania: SAE International, and Society of Automotive Engineers (SAE), *Cobalt Alloy, Corrosion and Heat Resistant, Welding Wire 39Co 22Cr 22Ni 14.5W 0.07La,* SAE AMS 5801D, Warrendale, Pennsylvania: SAE International. For helpful information about cobalt alloys, see Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

cubic, which is termed the *beta (β) phase*. The transformation temperature, sometimes referred to as the *beta transus*, is a function of the chemical composition of the beta phase. Aluminum, oxygen, nitrogen, and carbon stabilize the alpha phase. Tin and zirconium are neutral, while the other metallic elements in titanium are beta stabilizers.

Hydrogen also stabilizes beta titanium. The stability at room temperature of the alpha and beta phases is a function of the chemical composition. The relative amounts and distribution of the phases control the properties of titanium and titanium weld metals. The decomposition of the beta phase is similar to that of austenite in steel. The transformation of beta is normally a diffusion-controlled nucleation and growth process, but it can become a martensitic-type shearing transformation on rapid cooling.

Unlike steel, the beta and alpha-beta titanium alloys are relatively soft but strengthen during an aging treatment. During aging, a precipitation hardening reaction occurs in which fine alpha particles form within the beta grains.

Titanium quickly forms a stable, tenacious oxide layer on a clean surface exposed to air, even at room temperature. This makes the metal naturally passive and provides a high degree of corrosion resistance to salt or oxidizing acids and an acceptable resistance to mineral acids. Titanium's strong affinity for oxygen increases with temperature, and the surface oxide layer increases in thickness. Above 1200°F (650°C), oxidation increases rapidly, and the metal must be well shielded from air to avoid contamination and embrittlement by oxygen and nitrogen.

Pure titanium has low tensile strength and is extremely ductile. Dissolved oxygen and nitrogen markedly strengthen the metal as do iron and carbon to a lesser degree. Hydrogen embrittles titanium. These elements may unintentionally contaminate the metal during processing or joining.[18]

Zirconium

The characteristics of zirconium are similar to those of titanium except that zirconium is 50% more dense. It has the same hexagonal close-packed crystal structure (alpha phase) up to about 1600°F (870°C), at which point it transforms to body-centered cubic (beta phase). The beta phase is stable to the melting point.

Zirconium is highly resistant to corrosive attack because it forms a stable, dense, adherent, and self-healing zirconium oxide film on its surface. A visible oxide forms in air at about 400°F (200°C), becoming a loose white scale upon long-time exposure over 800°F (425°C). Nitrogen reacts with zirconium slowly at about 700°F (370°C) and more rapidly above 1500°F (810°C).

Zirconium is strongly resistant to corrosive attack by most organic and mineral acids, strong alkalis, and some molten salts. It resists corrosion in water, steam, and seawater. At elevated temperatures and pressures, zirconium also resists corrosion by liquid metals. Zirconium weldments are used in the petrochemical, chemical processing, and food processing industries.

As zirconium has a low neutron absorption, it is used in nuclear reactors. In nuclear applications, boron and hafnium contents are maintained at low levels because they have high neutron absorption. Nuclear welding operations must be performed in a vacuum-purged welding chamber, which can be evacuated and then backfilled with high-purity inert gas. An alternative to this procedure is to purge the chamber continuously with high-purity inert gas.[19]

Hafnium

Hafnium is used primarily to resist corrosion, to absorb neutrons in nuclear reactor control rods, and to contain spent nuclear fuel in reprocessing plants. A sister element to zirconium, hafnium possesses a hexagonal-close-packed crystal structure up to 3200°F (1760°C) and a body-centered-cubic structure above this temperature. It is three times as dense as titanium and superior to zirconium in resisting corrosion in water, steam, and molten alkali metals. In addition, it resists dilute hydrochloric and sulfuric acids, various concentrations of nitric acid, and boiling or concentrated sodium hydroxide.

Hafnium is readily welded using the processes and procedures used for titanium. Its low coefficient of expansion causes little distortion. Its low modulus of elasticity assures low residual welding stresses. Welded joints in metal 3/4 in. (19 mm) thick normally do not crack unless grossly contaminated.

Hafnium is severely embrittled by relatively small amounts of nitrogen, oxygen, carbon, or hydrogen. Thus, joint faces to be welded should be abraded using

18. The titanium filler metal specification is American Welding Society (AWS) Committee on Filler Metal, *Specification for Titanium and Titanium Alloy Welding Rods and Electrodes,* ANSI/AWS A5.16, Miami: American Welding Society. The procedures for welding titanium and its alloys are discussed in Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of *Welding Handbook,* Miami: American Welding Society. See also American Welding Society (AWS) Committee on Piping and Tubing, *Recommended Practices for Gas Tungsten Arc Welding of Titanium Piping and Tubing,* ANSI/AWS D10.6-91, Miami: American Welding Society.

19. Zirconium welding filler metals are addressed in American Welding Society (AWS) Committee on Filler Metal, *Specification for Zirconium and Zirconium Alloy Welding Rods and Electrodes,* ANSI/AWS A5.24-90, Miami: American Welding Society. Zirconium welding and brazing are discussed in more detail in Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of *Welding Handbook*, Miami: American Welding Society.

stainless steel wool or a draw file. The workpieces should then be cleaned with a suitable solvent and immediately placed in a vacuum-purge chamber. The chamber should at once be evacuated to 10^{-4} torr (13.3 MPa) and backpurged with inert gas. High-frequency arc starting prevents tungsten contamination from the gas tungsten arc welding electrode.

To verify the welding procedure and the purity of the welding atmosphere, sample welds made prior to production welding should be capable of being bent 90° around a radius three times the thickness of the weld sample.

Tantalum

Tantalum has a body-centered cubic crystal structure up to the melting point. It is an inherently soft, fabricable metal that is categorized as a refractory metal because of its high melting temperature. Unlike many body-centered-cubic metals, tantalum retains good ductility to very low temperatures and does not exhibit a ductile-to-brittle transition temperature. It has excellent corrosion resistance in a variety of acids, alcohols, chlorides, sulfates, and other chemicals. It is also used in electrical capacitors and for high-temperature furnace components.

Tantalum oxidizes in air above approximately 570°F (300°C). It is attacked by hydrofluoric, phosphoric, and sulfuric acids as well as by chlorine and fluorine gases above 300°F (150°C). Tantalum also reacts with carbon, hydrogen, and nitrogen at elevated temperatures. When dissolved interstitially, these elements and oxygen increase the strength properties and reduce the ductility of tantalum.

Tantalum is produced in powder-metallurgy, vacuum-arc-melted, and electron-beam-melted forms. The latter two products are recommended for welding applications. The welding of powder metallurgy material is not recommended because the weld would be very porous.

Tantalum alloys are strengthened by solid solution, by dispersion or precipitation, and by combinations of these methods. Some tantalum alloys have intentional carbon additions that respond to thermal treatments during processing. Their strength is derived from carbide dispersion and solution strengthening.

Tantalum and its alloys should be thoroughly cleaned prior to welding or brazing. Rough edges to be joined should be machined or filed smooth prior to cleaning. Components should be degreased with a detergent or suitable solvent and chemically etched in mixed acids. A solution composed of 40% nitric acid, 10% to 20% hydrofluoric acid, up to 25% sulfuric acid, and the remaining 15% to 25% water is suitable for pickling, followed by hot and cold rinsing in deionized water and spot-free drying. The cleaned components should be stored in a clean room with low humidity until they are ready for use.

Tantalum and tantalum alloys are readily welded using the processes and procedures described for titanium. Contamination by oxygen, nitrogen, hydrogen, and carbon should be avoided to prevent the embrittlement of the weld. Preheating is not necessary.

The high melting temperature of tantalum can result in metallic contamination if fixturing contacts the tantalum too close to the weld joint. Copper, nickel-alloy, or steel fixturing could melt and alloy with the tantalum. If fixturing is required close to the joint, a molybdenum insert should be used in contact with the tantalum. Graphite should not be used for fixturing because it will react with hot tantalum to form carbides.

The resistance spot welding of tantalum is feasible, but adherence and alloying between copper-alloy electrodes and tantalum sheet is a problem. Welding under water might be helpful because of the improved cooling of the copper electrodes. The weld time should not exceed 10 cycles (60 Hz). Tantalum can also be explosion welded to steel for cladding applications. Special techniques are required for the welding of tantalum-clad steel to prevent the contamination of the tantalum.

Nickel-based filler metals such as the nickel-chromium-silicon alloys form brittle intermetallic compounds with tantalum. Such filler metals are satisfactory for service temperatures only up to about 1800°F (980°C).[20]

Niobium

Niobium, formerly known as *columbium*, is both a reactive metal and a refractory metal with characteristics similar to those of tantalum. It has a body-centered-cubic crystal structure and does not undergo allotropic transformation. Its density is only half that of tantalum and its melting temperature is lower. Niobium oxidizes rapidly at temperatures above approximately 750°F (400°C) and absorbs oxygen interstitially at elevated temperatures, even in atmospheres containing small concentrations. It absorbs hydrogen between 500°F and 1750°F (260°C and 950°C). The metal also reacts with carbon, sulfur, and the halogen gases at elevated temperatures. It forms an oxide coating in most acids that inhibits further chemical attack. Exceptions are diluted strong alkalis and hydrofluoric acid.

The heat treatment of niobium should be performed in a high-purity inert gas or in high vacuum to avoid contamination by the atmosphere. The vacuum is generally the more practical. Niobium alloys containing zirconium respond to aging after a solution treatment. Fusion welds in such alloys are sensitive to aging during

20. For an extensive discussion of brazing techniques for tantalum, see Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2,* Vol. 4 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

service in the range of 1500°F to 2000°F (810°C to 1100°C).

Niobium and its alloys can be cleaned and pickled using the solvents and etchants described for tantalum. Cleaned components should be stored in a clean room under low-humidity conditions.

Most niobium alloys have good weldability, provided the tungsten content is less than 11%. With higher tungsten content in combination with other alloying elements, weld ductility at room temperature can be low. The processes, equipment, procedures, and precautions generally used to weld titanium are also suitable for niobium. One exception is welding in the open with a trailing shield. Although niobium can be welded with this technique, contamination is more likely because of the high temperature of the weld zone. Therefore, it is not recommended.

Those alloys that are prone to aging should be welded at relatively high travel speeds with the minimum energy input needed to obtain desired penetration. Copper backing bars and hold-downs can be used to extract heat from the completed weld. The purpose of these procedures is to minimize aging.

The gas tungsten arc welding of niobium should be performed in a vacuum-purged welding chamber backfilled with helium or argon. Helium is generally preferred because of the higher arc energy. Contamination by the tungsten electrodes should be avoided either by using a welding machine equipped with a suitable arc-initiating circuit or by striking the arc on a run-on tab.

The resistance spot welding of niobium presents the same difficulties as those encountered with tantalum. Electrode sticking can be minimized by making solid-state pressure welds between two sheets rather than actual nuggets. Projection welding might be an alternative to spot welding, but shielding may be required to avoid contamination by the atmosphere. Cooling the spot welding electrodes with liquid nitrogen substantially decreases electrode sticking and deterioration.

Molybdenum and Tungsten

Molybdenum and tungsten have very similar properties and weldability characteristics. Both metals have a body-centered-cubic crystal structure and exhibit a transition from ductile to brittle behavior with decreasing temperature. The transition temperature is affected by strain hardening, grain size, chemical composition, and other metallurgical factors.

The ductile-to-brittle transition temperature of recrystallized molybdenum alloys varies from below to well above room temperature. The transition temperature of tungsten is above room temperature. Consequently, fusion welds in these metals and their alloys have little or no ductility at room temperature. In addition, preheating to near or above the transition temperature may be necessary to avoid cracking from thermal stresses.

These metals and their alloys are consolidated by powder metallurgy and sometimes by melting in vacuum. Wrought forms produced from vacuum-melted billets generally have lower oxygen and nitrogen contents than those produced from billets manufactured by powder metallurgy methods.

Molybdenum and tungsten have low solubilities for oxygen, nitrogen, and carbon at room temperature. Upon cooling from the molten state or from temperatures near the melting point, these interstitial elements are rejected as oxides, nitrides, and carbides. If the impurity content is sufficiently high, a continuous brittle film forms at the grain boundary, severely limiting plastic flow at moderate temperatures. Warm working below the recrystallization temperature breaks up these grain-boundary films, producing a fibrous grain structure. The warm-worked structure has good ductility and strength parallel to the direction of working, but it may have poor ductility transverse to the working direction.

The interstitial compounds may dissolve in the grain-coarsened weld metal and the heat-affected zone of warm-worked molybdenum and tungsten alloys. Upon cooling, the compounds may precipitate at the grain boundaries. At the same time, grain growth and an accompanying reduction in surface area of the grain boundary take place. As a result, the weld metal and heat-affected zones are weaker and less ductile than the warm-worked base metal. The ductility of a welded joint is intimately related to the amount of interstitial impurities present and to the recrystallized grain size. Tungsten is inherently more sensitive to interstitial impurities than molybdenum. Welds that are ductile at room temperature have been produced in molybdenum. However, tungsten welds are brittle at room temperature.

Oxygen and nitrogen may be present in the metal. Alternatively, they may be absorbed from the atmosphere during welding. Thus, welding should be performed in a high-purity inert atmosphere or in high vacuum. Because grain size influences the distribution of the grain boundary films that are associated with brittleness, welding should be controlled to produce fusion zones and heat-affected zones of minimum width.

Molybdenum and tungsten are sensitive to the rate of loading and stress concentration. The ductile-to-brittle transition temperature of molybdenum and tungsten increases with increasing strain rates. Welded joints are notch sensitive; therefore, the weld surface should be finished smooth and faired gradually into the base metal wherever possible. Notches at the root of the weld should be avoided.

The mechanical properties of molybdenum and tungsten welds are not improved by heat treatment, but the alloys can be stress relieved at temperatures just below the recrystallization temperature. This should reduce the likelihood of cracking during subsequent handling.

Beryllium

Beryllium has a hexagonal-close-packed crystal structure, which partly accounts for its limited ductility at room temperature. Its melting point is 2332°F (1278°C) as compared to aluminum and magnesium, with melting points of 1220°F (660°C) and 1200°F (649°C), respectively. The specific heat of beryllium is about twice that of aluminum and magnesium. Its density is about 70% that of aluminum, but its modulus of elasticity is approximately four times greater. Therefore, beryllium is potentially useful for lightweight applications in which good stiffness is required. It is used in many nuclear energy applications because of its low neutron cross section.

Beryllium mill products are normally made by powder metallurgy. Wrought products are produced from billets manufactured by casting or powder metallurgy techniques. Cold-worked material may have good ductility in only one direction, and poor ductility perpendicular to that direction. Tensile properties may vary greatly, depending on the manner of processing.

As is the case with aluminum and magnesium, an adherent refractory oxide film rapidly forms on beryllium. This oxide film inhibits wetting, flow, and fusion during welding and brazing. Therefore, workpieces must be adequately cleaned prior to joining. The joining process must be shielded by inert gas or vacuum to prevent oxidation.

Intergranular microcracking in beryllium welds is caused by the grain boundary precipitation of binary and ternary compounds containing residual elements such as aluminum, iron, and silicon. If aluminum and iron are present as aluminum iron beryllium (AlFeBe), they are less detrimental. Therefore, by controlling the ratio of aluminum and iron atoms and maintaining low levels of these residuals, microcracking can be reduced.

The fusion welding processes that produce the smallest weld zones usually provide the best results in the welding of beryllium. Electron beam welding, with its characteristic low heat input, produces a narrow heat-affected zone with minimal grain growth and low distortion. Beryllium can also be joined by means of diffusion welding. Silver-coated samples can be joined successfully at low pressures and low temperatures in as little as 10 minutes.

CORROSION IN WELDMENTS

When predicting or calculating the corrosion service life of a fabrication, special consideration should be given to the microstructural features of the welds. Compositional variations—the effects of segregation and dilution—occur at the weld fusion and weld interface and in the heat-affected zone (HAZ). These variations often cause the weld to respond to corrosive environments very differently than the base material. Welding procedures and filler metal additions may also affect the corrosion resistance of weldments. Microsegregation and macrosegregation may even affect the corrosion rate within the same weld region.

The fusion zone, which exhibits the largest variation from the chemistry of the base metal, may disclose corrosion characteristics that are very different from an adjacent region in the HAZ. Differing thermal cycles in the HAZ result in element gradients and microstructural variations throughout this region. Weld defects, both subsurface (e.g., liquation cracking) and exposed (e.g., incomplete penetration), may also affect the corrosion resistance of weldments. Each of these heterogeneities and differing characteristics must be considered and understood when determining the corrosion service life of weldments.[21]

With the exception of some noble metals, all metals are subject to the deterioration effects of corrosion.

TYPES OF CORROSION

The common low-temperature forms of corrosion associated with microstructure and compositional variations are examined below.[22]

General Corrosion

If corrosion proceeds uniformly over a metal surface, the attack is classified as *general corrosion* or *uniform corrosion*. In general corrosion, the anode areas on the metal surface shift to different locations until the entire metal surface has been anodic at some time. Corrosion occurs at a given point on a group of readily dissolved atoms until this group is depleted. The point of attack subsequently moves to some other location. As corrosion progresses, an overall thinning of the metal occurs.

As with all types of corrosion, many factors influence the rate of attack. The corrosive media is the most important factor governing corrosion. Others include acidity, temperature, concentration, the motion relative

21. For more information on corrosion in weldments, see ASM International, 1987, *Corrosion,* Vol. 13 of *ASM Handbook*, Materials Park, Ohio: ASM International; INCO Alloys International, 1985, *Resistance to Corrosion,* Huntington, West Virginia: INCO Alloys International, pp. 5–11; and Neely, J. E., 1984, *Practical Metallurgy and Materials of Industry,* 2nd ed., New York: John Wiley and Sons, pp. 311–314.

22. For further information on corrosion details, see ASM International, 1987, *Corrosion,* Vol. 13 of *ASM Handbook,* Materials Park, Ohio: ASM International.

to metal surface, the degree of oxidizing power and aeration, and the presence or absence of inhibitors or accelerators.

Most of the factors involved in corrosion interact for a compound effect, and often this interaction is very complex. Aeration, for instance, interacts in two ways during the corrosion of iron in water. Oxygen can behave as a depolarizer and increase the rate of corrosion by accelerating the cathodic reaction. It can also behave as a passivator as it promotes the formation of a stable, passive film. As a rule, increases in temperature increase reaction rates. However, increasing temperature also tends to drive dissolved gases out of solution, so a reaction that requires dissolved oxygen can often be slowed by heating.

Galvanic Corrosion

When dissimilar metals are in electrical contact in an electrolyte, the less noble metal is attacked to a greater degree than if it were exposed alone. This attack is known as *galvanic corrosion* because the entire system behaves as a galvanic cell. Galvanic corrosion usually appears as furrows or troughs on the corroded metal at its point of contact with the more noble metal.

The following repair procedure provides a good example of galvanic corrosion. The weld repair of cast iron with nickel-based alloys is common practice throughout the fabrication industry. Nickel-based filler materials are used because they produce weld deposits that are capable of containing many of the elements in a cast iron in solid solution, and thermal expansion difficulties are less severe. Cast iron material is anodic relative to the nickel-based material. As a result, corrosion begins in the cast material neighboring the nickel-based weld deposit. Fabricators recommend that weldments with this combination be coated with a suitable protectant to reduce corrosion susceptibility.

Concentration-Cell or Crevice Corrosion

All natural processes tend toward an equilibrium state. Whenever conditions of nonequilibrium exist, there is a tendency to restore the more stable equilibrium state. Within a chemical system, when variations in the concentration of dissolved matter represent a nonequilibrium state, diffusion or other processes attempt to restore balance. At a crevice or shielded area (e.g., lack of penetration in a weldment), diffusion is limited and other processes play a greater role.

For instance, within a crevice, some metal may be dissolved and go into solution as metal ions. Outside the crevice, the same process occurs, but the relative amounts of solution result in a lower concentration outside the crevice than within. The metal just outside the crevice begins to go into solution at a more rapid rate in an attempt to balance this concentration. In other words, the metal outside the crevice is anodic to the metal within the crevice, and this potential difference supports a current. If the solution is in motion, the ions are carried away as they are produced, preventing equilibrium and permitting corrosion to continue.

Prevention techniques are numerous. The publication *Resistance to Corrosion*[23] provides further information regarding these techniques.

Intergranular Corrosion

Intergranular corrosion consists of a localized attack along the grain boundaries of a metal or alloy. Corrosion can proceed to the point where whole grains of metal fall away and the metal loses its strength through a reduction in cross section. Intergranular corrosion is usually caused by an improper heat treatment or by heat from welding that in turn causes the precipitation of certain alloy components at the grain boundary. This precipitation causes a depletion of corrosion-resisting elements in the area surrounding the grain boundary, and this area becomes anodic to the remainder of the grain.

This form of attack is most common with austenitic stainless steels. The precipitate is a chromium carbide that appears at the grain boundaries during heating and cooling or exposure at temperatures between 800°F and 1400°F (427°C and 760°C). The depleted component is chromium, and attack occurs in the chromium-depleted areas.

Four methods can be implemented to combat intergranular corrosion in areas where susceptible materials must be heated in the sensitizing range. The first method involves reheating the metal to a temperature high enough to dissolve the precipitated phase and subsequently cooling it quickly enough to maintain this phase in solution. The second method, known as *stabilization*, consists of adding certain elements (niobium, tantalum, and titanium, for example) that combine more effectively with carbon than chromium. In this way, chromium is not depleted, and the metal retains its corrosion resistance.

The third method is to restrict the amount of one of the constituents of the precipitate, usually carbon, thereby curtailing precipitation and the resulting alloy depletion. The fourth method involves keeping the welding heat input to a minimum. A welding procedure should be developed for a welding process and electrical settings to achieve a low heat input. The interpass temperature should be as low as possible, sometimes as low as 250°F (121°C). In stainless steel, the chromium carbides precipitate at time and temperature. The degree of

23. INCO Alloys International, 1985, *Resistance to Corrosion*, Huntington, West Virginia: INCO Alloys International.

grain boundary sensitization is minimized by minimizing the amount of time the weldment is heated into the carbide precipitation temperature range.

Stress Corrosion Cracking

Stress corrosion cracking can occur in weldments when susceptible microstructure, surface tensile stresses, and corrosive media are all present simultaneously. As heat or energy input influences the size and geometry of the weld deposit, welding parameters and procedures affect the amount and distribution of residual stress present in the weld.

Pitting

Pitting is localized corrosive attack caused by the reduction of the protective thin passive oxide film. Pits typically result from a concentration cell that has formed from variations in a solution composition that is in contact with the material. Compositional variations occur when the solution at a surface discontinuity is different from the composition of the bulk solution.

Once formed, the pit acts as an anode supported by surrounding large cathodic areas. Pitting occurs when the solution or the material combination, or both, reach a potential that exceeds a critical value termed the *pitting potential.*

Pitting is site-selective and microstructure-dependent. It occurs or initiates more readily in heterogeneous material. A higher probability of local attack exists when a matching filler metal is used because of the segregation effects in the weld metal.

MINIMIZING SUSCEPTIBILITY TO CORROSION

An awareness of corrosive environments and an understanding of segregation effects and compositional differences as they relate to service life are necessary. Selection of the proper base metal and welding consumable by taking into account the properties of the material and environmental considerations contributes to reducing the possible deleterious effects of corrosion.

Welding Design and Practice

Welding procedures and techniques that provide complete joint penetration (where required) and a smooth, slightly convex weld geometry should be utilized. Incomplete or excessive penetration, undercut or underfill, porosity, hydrogen cracking, and so forth are susceptible initiation sites for corrosion. Weldments should be designed so that welds are placed in low-stress areas whenever possible. In addition, no residual slag or flux should remain on any portion of a completed weld deposit. Inter-layer grinding or chipping should be used to remove any oxide buildup.

Preweld or postweld thermal treatments should be utilized when applicable to reduce problems associated with stress and the effects of hydrogen embrittlement. Weld metal segregation effects can typically be reduced if the weldment can be solution annealed upon the completion of fabrication.

Surface Preparation

Surfaces to be welded should be cleaned prior to welding with an approved solvent, power wire brushing, or by other mechanical means. Surfaces should be free from grease, dirt, and other contaminants. Care must be taken when preparing surfaces to be welded. Grease, marking crayons, processing chemicals, oil, and paint are all potential sources of contamination which can lead to corrosion.

THE BRAZED OR SOLDERED JOINT

Brazing and soldering operations are performed at temperatures below the solidus of the base materials.[24] A basic advantage of brazing and soldering is that joining temperatures are below the melting temperature of the base metal. Therefore, base metal properties are less affected by the process, and residual stresses and distortion are lower. In addition, entire assemblies can be exposed to the process temperature, which is an economic benefit in production.

Several disadvantages are associated with brazing and soldering, however. The nondestructive examination of brazed and soldered joints is not easily performed. In addition, depending on the complexity of the components, fixturing may be required to keep the fit of workpieces within the close tolerances needed for brazing and soldering.

The metallurgical considerations that affect these processes range from the properties and solidification of liquid metal to base metal-surface interactions and the physical and environmental conditions under which the joints are made.

Brazing filler metals have a liquidus above 840°F (450°C), whereas soldering filler metals have a liquidus below this temperature. In both brazing and soldering, the filler metal is distributed between the closely fitted surfaces of the joint by capillary action. The capillary

24. Brazing and soldering processes are overviewed in Chapter 1 of this volume.

flow of the liquid metal into the joint generally depends upon its surface tension, wetting characteristics, and physical and metallurgical reactions with the base material and oxides involved. Capillary flow is also influenced by the generation of hydrostatic pressure within the joint.

Figure 4.33 presents a simplistic illustration of wetting, defined as "the phenomena whereby a liquid filler metal or flux spreads and adheres in a thin continuous layer on a solid base metal."[25] A contact angle of less than 90° measured between the solid and liquid usually indicates a positive wetting characteristic. Contact angles greater than 90° are usually an indication that no wetting has taken place.

In some brazing and soldering process variations, a controlled atmosphere facilitates wetting and spreading. Fuel gases, hydrogen, and vacuum systems provide the most common types of controlled atmospheres. In vacuum brazing, however, flow and wetting depend on favorable surface interaction between the liquid metal and the base metal.

In other process variations, wetting and spreading are assisted by the addition of flux. Fluxes perform functions similar to controlled atmospheres in providing surfaces receptive to wetting and spreading. Most oxides are readily displaced or removed by flux. Oxides of chromium, aluminum, titanium, and manganese are more difficult to remove by flux and may require special treatment.

A brazing or soldering cycle generally consists of heating to a peak temperature, maintaining that temperature for a specified duration, and then cooling. During the time at peak temperature when liquid filler metal is present in the joint, metallurgical reactions can occur with the base metal. These reactions are generally referred to as *erosion* or *dissolution*. The rate of dissolution of the base metal by the filler metal depends on the mutual solubility limits, the quantity of brazing filler metal available to the joint, the brazing cycle, and the potential formation of lower temperature eutectics.

In some important metallurgical systems, an interlayer of intermetallic compound forms between the filler metal and the base metal during the joining operation. The degree of intermetallic growth and the type of phases present can substantially alter the properties of the joint. Phase diagrams can be used to predict the formation of intermetallic compounds.

Once the filler metal has solidified to form the joint, subsequent effects are controlled by diffusion phenomena within the joint. It is possible to convert the filler metal into an intermetallic compound through the high-temperature aging of a soldered joint. For example, when titanium is joined with a pure tin filler metal, the

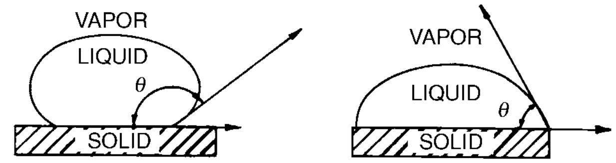


Figure 4.33—Wetting Angles of Brazing and Soldering Filler Metals

application of a subsequent aging or heat treatment diffuses the tin into the base metal completely so that the joint effectively ceases to exist. Although this method of metallurgical joining has been termed *liquid-activated diffusion welding*, it is actually an extension of the joining mechanism used in brazing and soldering.

Impurities and contaminants are important factors to be considered with these processes. Contamination caused by mishandling materials or resulting from joint preparation can affect the formation of the joint and the joint properties. For example, residual sulfur compounds can cause poor flow or result in hot cracking in certain brazed or soldered joints.

The properties of brazed joints depend upon successful metallurgical bonding at the interfaces and on the final composition of the brazed metal in the joint area. Most joints of this type are designed with a large factor of safety to ensure satisfactory performance in service. However, the metallurgical properties of the joint can be important when high-temperature service or exposure to corrosive media is anticipated.

Strength measurements of brazed and soldered joints are conducted in shear, in tension using a peel method, or by hardness traverses across the joint area. The dynamic properties of these joints are measured under creep, fatigue, and stress-corrosion conditions. Consideration must be given to all these factors when selecting a suitable brazing or soldering filler metal. In addition, extreme care is necessary when interpreting destructive tests of brazed and soldered joints because results are influenced by factors unique to the tested joint. These include joint geometry and overlap, joint soundness, and variation of testing procedures.

A problem often observed in brazed joints is the penetration of liquid filler metal between the grain boundaries of the base metal. If excessive, this penetration can lead to embrittlement. Base materials in a stressed state are particularly susceptible to liquid metal penetration. For example, when copper-based filler metals are used

25. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, AWS 2001, Miami: American Welding Society, p. 86.

on high iron-nickel alloys under stress, rapid failure can result. The diffusion rate of alloying elements is greater in grain boundaries than in the crystal lattice. Therefore, the intergranular penetration of brazing filler metal atoms is greater than the transgranular penetration.

If a eutectic is formed, it may fill any grain boundary crack as it separates. In this case, the joint sustains little damage. This phenomenon is known as an *intrusion*. Where high solubility exists, intergranular attack is typically less intense. When rapid failure of a joint or adjacent material occurs during the manufacturing operation, boundary penetration phenomena should be suspected.

The dynamic characteristics of the brazing and soldering processes should be recognized, and careful consideration must be given to the subsequent diffusion and metallurgical changes that can occur in service. At elevated temperatures, intermetallic compounds still grow in the solid state as a direct result of diffusion. Thus, the metallurgical and mechanical properties of these joints can change in service.

BRAZING AND SOLDERING ALLOYS

Several commercially available alloys used in brazing and soldering operations are discussed below.

Brazing Alloys

A brazed joint must have the appropriate physical and mechanical properties for the intended service application. The brazing process, the base metal, and the filler metals are selected to meet these needs. An important qualification for filler metal is the compatibility of the melting range with that of the base metal.

A source of information on brazing filler metals is *Specification for Filler Metals for Brazing and Braze Welding* ANSI/AWS A5.8,[26] published by the American Welding Society and approved by the American National Standards Institute (ANSI). This specification has been adopted by the United States Department of Defense. Brazing filler metals and solders are commercially available to join most industrial metals and alloys. Several alloys are discussed below. Additional information on brazing is available in the *Brazing Handbook*.[27]

Tantalum. The successful brazing of tantalum and its alloys depends upon the application. For corrosion applications, the brazed joint must also be corrosion resistant. Commercially available filler metals are not as resistant to corrosion as tantalum. For high-temperature applications, the brazed joint must have a high remelt temperature as well as adequate mechanical properties at the service temperature.

Tantalum must be brazed in a high purity inert atmosphere or in high vacuum. Special equipment is usually required for high-temperature brazing. For low-temperature brazing, the tantalum can be plated with another metal such as copper or nickel, which are both readily wet by the brazing filler metal. The brazing filler metal should alloy with and dissolve the plating during the brazing cycle.

Tantalum forms brittle intermetallic compounds with most commercial brazing filler metals. The composition of the filler metal, the brazing temperature, and the heating cycle affect the degree of interaction between the two metals. In general, the brazing time should always be the minimum unless diffusion brazing techniques are used.

Niobium. Niobium-alloy brazements are used in high-temperature service. Brazing temperatures range from 1900°F to 3450°F (1040°C to 1900°C). Filler metals readily wet and flow on the niobium in a vacuum. In some systems, the strength of the brazement is improved by a diffusion heat treatment.

Molybdenum and Tungsten. Many brazing filler metals can be used to join molybdenum or tungsten, whose brazing temperatures range from 1200°F to 4500°F (650°C to 2480°C). The chosen brazing filler metal must be evaluated by means of the appropriate tests for a specific application. In many cases, the service temperature limits the choice. The effects of brazing temperature, diffusion, and alloying on the base metal properties must also be determined. The brazing time should be as short as possible to minimize recrystallization and grain growth in the base metal.

Beryllium. Beryllium can be joined by brazing and by braze welding. However, because of the oxide film on the surface of the metal good capillary flow is difficult to achieve. Filler metals with low melting temperatures, such as aluminum-silicon and silver-based alloys, are normally recommended. Filler metals should be preplaced in the joint for best results. Brazing times should be short to minimize alloying and grain boundary penetration.

Soldering Alloys

The integrity of a soldered joint depends on the base metal, interface reactions, and the geometry of the joint combined with the properties of the solder alloys. The density of the solder, its electrical and thermal

26. American Welding Society Committee on Filler Metal, *Specification for Filler Metals for Brazing and Braze Welding,* ANSI/AWS A5.8, Miami: American Welding Society.

27. American Welding Society (AWS) Committee on Brazing and Soldering, 20XX, *Brazing Handbook,* 5th ed., Miami: American Welding Society.

properties, and its fluidity are considerations in the selection of a solder for a particular application.

Soldering alloys[28] are commercially available in a variety of compositions and are grouped in more than ten classifications. Any composition, weight, size, or shape can usually be custom made. Specifications for solder alloys are published by the American Society for Testing Materials (ASTM) in *Standard Specification for Solder Metal*, ASTM B-32.[29]

Tin-Lead. Most commonly used are the tin-lead solder alloys in compositions ranging from 5% tin and 95% lead to 30% tin and 70% lead (stated as 5/95 and 30/70, as the tin content is customarily identified first). Melting temperatures as well as wetting and flow characteristics change with the ratio of tin to lead. Impurities may enter the solder during manufacture or the solder may be contaminated during use. Elements such as aluminum, antimony, arsenic, bismuth, cadmium, copper, iron, nickel, phosphorous, sulfur, and zinc are considered to be impurities in tin-lead solders, although antimony may be used in place of some of the tin to improve the mechanical properties of the joint.

Tin-Silver and Tin-Copper-Silver. Alloys of tin-silver and tin-copper-silver are examples of solders used when lead is undesirable in the application, such as for joining copper pipe and tubes in potable water systems. Tin-lead-silver solders are capable of joining silver-coated materials often used in the electronics industry. Tin-zinc solders in various compositions are commonly used to join aluminum.

Cadmium-Silver and Cadmium-Zinc. Cadmium-silver alloys are useful for copper joints and for joining aluminum. Cadmium-zinc and zinc based solders, such as alloys of zinc-aluminum were developed specifically to join aluminum.[30]

CORROSION IN BRAZED AND SOLDERED JOINTS

Stress corrosion cracking has been encountered in brazements of high-strength alloys when annealing temperatures are above the melting temperature of the brazing alloy. For example, silver in the molten state can be considered a corrosive medium. Stress cracking, which is readily detected by visual examination, occurs almost instantaneously at the brazing temperature. No further cracking typically occurs after the workpieces have cooled.

Cold forming (drawing, bending, spinning, and so forth) can sometimes produce sufficient internal stress to cause cracking during brazing. Improper fixturing is often to blame. Stress can be applied by a fixture that fails to provide proper alignment of workpieces or one that clamps the workpieces too tightly. Unequal, rapid heating also can create sufficient stress to induce cracking. If heavy workpieces are heated so rapidly that the outside surfaces become hot without appreciable heating of the center, thermal stresses are set up, and stress cracking may occur.[31]

Stress-corrosion cracking can be eliminated or susceptibility to cracking can be reduced by making changes in procedure. Typical procedural changes include the following:

1. Using annealed rather than hard-temper material;
2. Annealing cold-worked workpieces before brazing;
3. Eliminating externally applied stress;
4. Heating at a slower, more uniform rate;
5. Using a higher-melting-point braze alloy (to provide some stress relief of the base material during heating, before the brazing alloy melts);
6. In torch brazing, heating the fluxed and assembled workpieces to a high temperature (1600°F [870°C]) and then cooling to the appropriate temperature before applying the brazing alloy; and
7. Using an alloy that does not contain cadmium (an addition that causes no cracking by itself but can aggravate the conditions conducive to cracking).

CONCLUSION

A thorough knowledge of welding metallurgy is critical to the production and reproduction of high-quality welds and brazed and soldered joints. Welding metallurgy and its application are also crucial when considering, implementing, and participating in research and development programs with the aim of developing new and improved welding products. Process effects and base- and filler-metal compatibility also play vital roles when providing technical support to customers and manufacturing divisions. Product design issues com-

28. For further information on soldering and soldering alloys, refer to Manko, H. H., 1979, *Solders and Soldering,* 2nd ed., New York: McGraw Hill.
29. American Society for Testing and Materials (ASTM), *Standard Specification for Solder Metal*, ASTM B-32, West Conshohocken, Pennsylvania: American Society for Testing Materials.
30. Vianco, P. T., 2000, *Soldering Handbook,* 3rd ed., Miami: American Welding Society.
31. More information on stress corrosion cracking is presented in INCO Alloys International, 1985, *Resistance to Corrosion*, Huntington, West Virginia: INCO Alloys International, pp. 23–31.

monly include a material's mechanical properties tested at ambient and elevated temperatures and the effects that processing, heat treatment, and welding have on the microstructure a given material.

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CHAPTER 5

DESIGN FOR WELDING

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CHAPTER 5

DESIGN FOR WELDING

INTRODUCTION

A weldment is an assembly of component parts joined by welding. It may be a bridge, a building frame, an automobile, a truck body, a trailer hitch, a piece of machinery, or an offshore oil drilling structure. In the field of weldment design,[1] the primary objectives are to produce an assembly that (1) performs its intended functions, (2) has the required reliability and safety, and (3) can be fabricated, inspected, transported, and placed in service at a minimum total cost. The total cost includes the cost of design, materials, fabrication, erection, inspection, operation, repair, and product maintenance.

The designers of weldments must have an understanding of basic design principles and concepts. They must have some knowledge of and experience in cutting and shaping metals; assembling components; preparing and fabricating welded joints; evaluating welds in compliance with established acceptance criteria; and performing nondestructive examination and mechanical testing.[2] Designers routinely apply knowledge of the following areas when evaluating the effects these may have on the design of weldments:[3]

1. Mechanical and physical properties of metals and weldments;
2. Weldability of metals;
3. Welding processes, costs, and variations in welding procedures;
4. Filler metals and properties of weld metals;
5. Thermal effects of welding;
6. Effects of restraint and stress concentrations;
7. Control of distortion;
8. Efficient use of steel, aluminum, and other metals in weldments;
9. Design for appropriate stiffness or flexibility in welded beams and other structural members;
10. Design for torsional resistance;
11. Effects of thermal strains induced by welding in the presence of restraints;
12. Effects of stress induced by welding in combination with design stresses;
13. Practical considerations of welding and the selection of proper joint designs for the application.
14. Communication of weldment design to the shop, including the use of welding symbols; and
15. Applicable welding codes and safety standards.

As several of these topics involve highly specialized areas of science and technology, designers should refrain from relying entirely upon their own knowledge and experience, which may be may generalized. They are encouraged to consult with welding experts whenever appropriate.

1. Of necessity, the topics discussed in this chapter have not been developed exhaustively. For more information, the reader should refer to available textbooks, manuals, and handbooks, several of which are listed in the Bibliography and the Supplementary Reading List at the end of this chapter.

2. A great deal of similarity exists between the designs of weldments and brazements, with the exception of joint designs and the joining processes. Consequently, much of the information presented in this chapter can also be applied to brazement design. For more information, refer to O'Brien, R. L., ed., *Welding Processes*, 1991, Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

3. The topics listed here are covered in this volume as well as in O'Brien, R. L., ed., *Welding Processes*, 1991, Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society; Oates, W. R., ed., 1996, *Materials and Applications—Part 1*, Vol. 3 of *Welding Handbook,* Miami: American Welding Society; and Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2,* Vol. 4 of the *Welding Handbook,* 8th edition: Miami: American Welding Society.

PROPERTIES OF METALS

The properties of metals can be divided into five general groups: (1) mechanical, (2) physical, (3) corrosion, (4) optical, and (5) nuclear. The typical characteristics of each group are presented in Table 5.1. These are further categorized as structure-insensitive or structure-sensitive, as this distinction is made in most textbooks

Table 5.1
Properties of Metals

General Groups of Properties	Structure-Insensitive Properties	Structure-Sensitive Properties
Mechanical	Elastic moduli	Ultimate strength
		Yield strength
		Fatigue strength
		Hardness
		Ductility
		Elastic limit
		Damping capacity
		Creep strength
		Rupture strength
		Toughness
Physical	Thermal expansion	Thermal stresses
	Thermal conductivity	
	Melting point	
	Specific heat	
	Emissivity	
	Thermal evaporation rate	
	Density	
	Vapor pressure	
	Electrical conductivity	
	Thermoelectric properties	
	Magnetic properties	Ferromagnetic properties
	Thermionic emission	
Corrosion	Electrochemical potential	
		Oxidation resistance
Optical	Color	
	Reflectivity	
Nuclear		Radiation absorptivity
		Nuclear cross section
	Wavelength of characteristic X-rays	

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, Table 3.1.

on metals to highlight the considerations that should be given to the reported values of the properties.[4] Only those properties related to weldment design will be discussed in this chapter. These include the mechanical, physical, and corrosion properties.

The structure-insensitive properties of metals do not vary from one piece of a metal to another of the same composition, regardless of differences in microstructure. This has been verified by data obtained from standard engineering tests and is true for most engineering purposes. These properties can often be calculated or rationalized by examining the chemical composition.[5] The structure-insensitive properties are commonly considered constants for metals.[6]

The structure-sensitive properties are dependent not only upon the chemical composition and crystallographic structure but also upon microstructural details that may be affected in subtle ways by the manufacturing and processing history of the metal. Even the size of the sample can influence the test results obtained for a structure-sensitive property.[7] Structure-sensitive properties are likely to vary somewhat if differences exist in the treatment and preparation of the samples.

In the field of weldment design, the most important mechanical properties of metals, with the exception of the moduli of elasticity (see the section "Modulus of Elasticity" below), are those that are structure-sensitive. Consequently, the published single values of these properties should be considered with reservation. It is common for the mechanical properties of metal plates or bars that are unusual in size or treatment condition to deviate significantly from the values published for the particular metals. In addition, as determined by standard quality acceptance tests in an American Society for Testing and Materials (ASTM) specification, the mechanical properties of a metal do not guarantee identical properties throughout the material represented by the test sample.[8,9] For example, the direction in which wrought metal is tested (longitudinal, transverse, or through-thickness) may result in significantly different values for strength and ductility.

The physical and corrosion properties of metals are considered structure-insensitive for the most part. Some of the values established for these properties apply only to common polycrystalline metals, however.

4. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 133.

5. General metallurgy and welding metallurgy are covered in Chapter 4 of this volume.
6. See Reference 4.
7. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society.
8. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
9. American Society for Testing and Materials (ASTM), 1997, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A370-97a, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

MECHANICAL PROPERTIES

As metals are generally strong, tough, and ductile, they are advantageous construction materials. This combination of properties is rarely found in nonmetallic materials, so most nonmetallic construction materials depend upon composite action with metals for their usefulness. The strength, toughness, and ductility of metals can be modified by means of alloy or heat treatment. Metals offer not only many useful individual mechanical properties and characteristics but also a large number of combinations of these properties. This versatility allows designers to select the best combination of properties to ensure the intended performance level.

Among the factors that affect the mechanical properties of metals are applied heat, the cooling rate, the addition of filler metal, and the metallurgical structure of the joint.[10] The joining of metals by welding or brazing also affects their mechanical properties.

Another factor that must be considered during the materials selection process is ease of fabrication. Base metals and welding consumables should be selected to facilitate fabrication. When making a decision regarding the selection of materials, it is necessary to examine the governing properties of the metals and consider their combined effect upon the design and service behavior of the weldment.

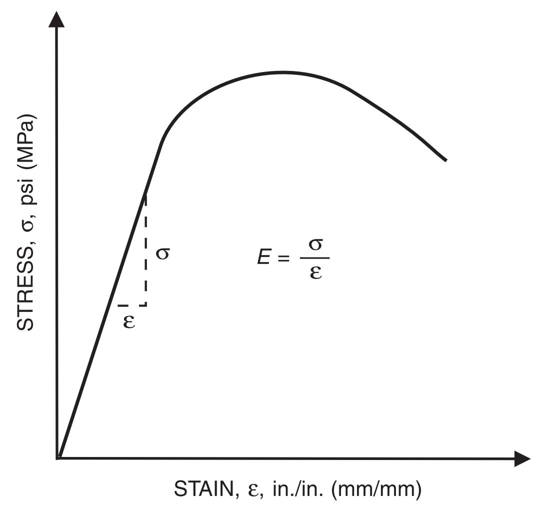


Figure 5.1—Young's Modulus (Modulus of Elasticity), *E*

Modulus of Elasticity

A convenient way to assess a metal's ability to resist stretching (strain) under stress in the elastic range is Young's Modulus, also known as the *modulus of elasticity.* This is the ratio between the applied strain and the resulting stress. In the elastic range, the modulus of elasticity, a constant, is expressed by the following equation:

$$E = \frac{\sigma}{\varepsilon} \tag{5.1}$$

where

- E = Modulus of elasticity;
- σ = Stress, pounds per square inch, psi (megapascal [MPa]), and
- ε = Strain, inch per inch (in./in.) (millimeter per millimeter [mm/mm]).

Young's Modulus, shown in Figure 5.1, can be calculated from the measured strain and calculated stress generated during a standard tension test. As the modulus of elasticity is a structure-insensitive property, it is not influenced by grain size, cleanliness, or heat treatment; in fact, the modulus of elasticity often remains unchanged even after considerable alloy additions have been made.[11]

Table 5.2 presents the modulus of elasticity for a number of metals.

For practical purposes, the modulus of elasticity can be used to determine the level of stress created in a piece of metal when it is forced to stretch elastically a specified amount. The stress can be determined by multiplying the strain by the modulus of elasticity. It is important to point out that the modulus of elasticity decreases with increasing temperature and that these temperature-influenced changes vary with different metals.

Elastic Limit

The elastic behavior of a metal reaches a limit at a level of stress termed the *elastic limit*. This is the highest stress a member can bear and still return to its original dimensions when the load is released. When the elastic limit is exceeded, the member permanently deforms. The elastic limit of a metal is structure-sensitive and dependent on the strain rate.

The design of many components is limited by the elastic limit. Therefore, several properties related to this limit have been defined. These properties can be deter-

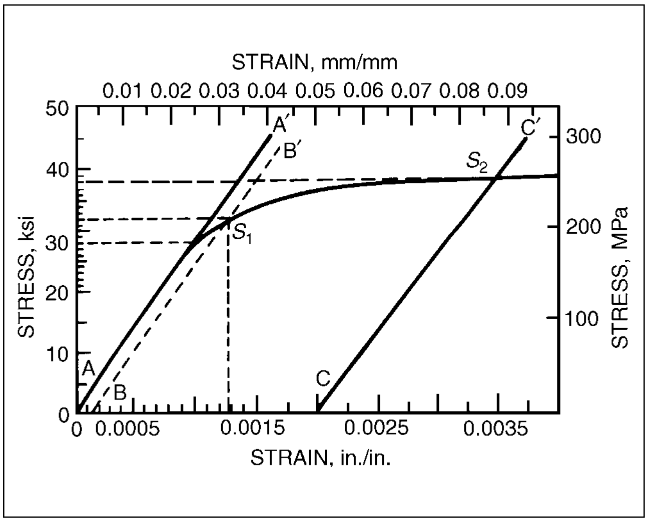
10. The testing and evaluation of welded joints are discussed in Chapter 6 of this volume.

11. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 139.

Table 5.2
Modulus of Elasticity of Metals

	Modulus of Elasticity	
Metal	**psi (10^6)**	**MPa (10^3)**
Aluminum	9.0	62.0
Beryllium	42.0	289.4
Niobium (columbium)	15.0	103.4
Copper	16.0	110.2
Iron	28.5	196.4
Lead	2.0	13.8
Molybdenum	46.0	316.9
Nickel	30.0	206.7
Steel, carbon, and alloy	29.0	199.8
Tantalum	27.0	186.0
Titanium	16.8	115.8
Tungsten	59.0	406.5

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Table 3.2.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 3.2.

Figure 5.2—Typical Tensile Stress-Strain Diagram for a Metal Stressed Beyond the Limit of Elastic Behavior

mined from the stress-strain diagram that is commonly plotted for a tension test. A typical diagram is presented in Figure 5.2.

The stress-strain curve is initially a straight line, which is indicated in Figure 5.2 as line A-A´. The slope of this line is the metal's modulus of elasticity. As the line proceeds upward, a point is reached at which the strain exceeds the amount predicted by the earlier straight-line relationship. It is difficult to determine the exact point at which the proportionality between stress and strain ends because the clarity and interpretation of the curve may vary. The elastic limit on the stress-strain curve shown in Figure 5.2 is approximately 28 kips per square inch (ksi) (190 MPa). This is the maximum point at which the strain remains directly proportional to stress.

When a metal is strained below the elastic limit, it recovers upon removal of the load. On the other hand, when a metal is stressed beyond its elastic limit, the additional strain is plastic in nature and results in permanent deformation. As an example, if the tensile specimen depicted in Figure 5.2 were loaded to 32 ksi (220 MPa), as shown in S_1, the specimen would elongate 0.00125 in./in. (.00125 mm/mm). Upon removal of the load, the specimen would not return to its original length but would display a permanent stretch of approximately 0.00015 in./in. (0.00015 mm/mm), represented by line B-B´.

Yield Strength

The yield strength of a metal is the stress level at which the metal exhibits a specified deviation from the proportionality of stress and strain. A practical method utilized to determine the yield strength of a metal is illustrated in Figure 5.2. Line C-C´ is drawn parallel to the elastic Line A-A´ from a point on the abscissa, representing 0.2% (0.0020 in./in. [0.0020 mm/mm]) elongation. Line C-C´ intersects the stress-strain curve at S_2, where the stress level is approximately 38 ksi (260 MPa). This stress is the yield strength of the tested metal. While an offset yield strength of 0.2% is commonly used in engineering design, offsets of 0.1% and 0.5% are sometimes employed in the same manner for various metals.

Tensile Strength

The ratio of the maximum load sustained by a tension test specimen to the original cross-sectional area is referred to as the *ultimate tensile strength* (*UTS*). The UTS is the most common value calculated from the standard tension test. However, the true tensile strength of a metal, which is the ratio of the breaking load to the final cross-sectional area, may be substantially higher than the reported tensile strength.

The tensile strength values obtained for metals are influenced by many factors. Tensile strength is a structure-sensitive property. It is dependent upon chemical composition, microstructure, the direction of rolling, grain size, and strain history. The size and shape of the specimen and the rate of loading can also affect the result. For these reasons, the UTS of the heat-affected zone may be different from that of the unaffected base metal.

Fatigue Strength

Behavior under cyclic loading is an important aspect of the strength of metals and welded joints. Fatigue fractures develop because the applied forces, even at nominal tensile stresses lower than yield-point stress, cause the tip of a crack to advance a minute amount. This phenomenon is termed *stable crack growth*. The rate of crack growth increases as the area ahead of the crack decreases until the crack reaches a critical size. At this point, unstable crack growth initiates, and sudden, complete failure follows.

Crack growth does not occur when the net stress at the crack tip is compressive, however. A crack may initiate due to high residual tensile stresses, but the formation of the crack will relieve the local stress condition. Thus, if the applied load is compressive, the crack will not grow to a critical size.

The stress that a metal can endure without sustaining fracture decreases as the number of repeated stress applications increases. Fatigue strength is generally defined as the maximum stress that can be sustained for a stated number of cycles without failure. As the number of cycles is increased, the corresponding fatigue strength becomes lower. The term *fatigue life*, accordingly, refers to the number of cycles of stress that can be sustained by a metal under stipulated conditions.

For a given stress level, the fatigue strength of steel is constant beyond approximately two million cycles. Several million additional cycles are required to cause a significant reduction in fatigue strength. Thus, for practical purposes, the fatigue limit is the maximum stress or stress range that a metal can bear for an infinite number of cycles without sustaining fracture. Such a limiting stress level is often called the *endurance limit*.

The endurance limits reported for metals in engineering handbooks are usually determined using polished round specimens tested in air. These data are valid and useful for design in applications such as shafts in rotating machinery and other uniform members. However, they may have little relevance in the design of weldments, as these are characterized by abrupt changes in cross section, geometrical and metallurgical discontinuities, and residual stresses, all of which adversely affect fatigue life.

Weldments in rotating equipment are particularly prone to fatigue failure. Pressure vessels can also fail by fatigue when the pressurization is cyclic and stress above the fatigue strength is concentrated at some point. When designing welded built-up members and welded connections for structures subject to fatigue loading, the applicable standard governing the subject structure must be followed. In the absence of a specific standard, the designs of existing welded components should be used as a guide.

Localized stresses within a structure may result entirely from external loading, or they may be caused by a combination of applied and residual stresses. Residual stresses are not cyclic, but they may augment or detract from applied stresses, depending upon their respective signs. For this reason, it may be advantageous to induce, if possible, compressive residual stress in critical areas of a weldment where cyclic applied tensile stresses are expected. This can be accomplished by a welding sequence that controls the residual stresses produced during welding or by a localized treatment that acts to place the surface in compression.

Thermal stresses must be considered in the same light as applied stress. Thermal stresses result from the expansion and contraction of a material during heating and cooling. As a metal is heated, it expands. If the material is restrained and not free to expand, thermal compressive stresses are formed. Conversely, if a restrained part is cooled, the result is a tensile stress. Thermal cycling can lead to fatigue failure if the thermal gradients are steep or if the thermal stresses are concentrated by a stress raiser, such as a change in cross section or a discontinuity.

In summary, the designers of weldments require a thorough understanding of the fatigue characteristics of metals as used in weldments. For weldments subject to loading in the tension range, the most common cause of fracture is fatigue. One of the reasons for this is the frequent presence of stress raisers, which concentrate imposed cyclic stresses to levels above the fatigue limit of the metal for the existing conditions.

Ductility

The amount of plastic deformation that an unwelded or a welded specimen undergoes in a mechanical test carried to fracture is considered a measure of the ductility of the metal or the weld. Values expressing ductility in various mechanical tests are meaningful only for the relative geometry and size of the test specimen. Thus, they do not measure any fundamental characteristic, but merely provide relative values for the comparison of the ductilities of metals subjected to identical test conditions. The plasticity exhibited by a specimen is simply the deformation accomplished during the yielding process. Regardless of the method of measurement, ductility is a structure-sensitive property. It is affected by many of the testing conditions. The size and shape of the specimen, ambient temperature, strain rate, microstructure, and surface conditions all influence the amount and location of plastic deformation prior to fracture.[12]

The ductility values derived from precise or elaborate tests are not used directly in weldment design. Structures are usually designed to function at stresses below the yield strength, and any serious deformation usually disqualifies the unit or article from service. Nonetheless, ductility values are useful in providing an indication of the ability of a metal to yield and relieve localized high stresses. They also provide insight into the reserve of plasticity available to ensure against sudden fracture under unexpected overloading. However, as most structures are sensitive to both loading rate and temperature, ductility values do not necessarily indicate the amount of plastic deformation that will take place under all conditions of loading.[13]

Fracture Toughness

A metal that is judged ductile by a standard tension or slow-bend test may perform in a brittle manner in another type of test or when exposed to service conditions. Thus, the only prediction that can be made with reasonable certainty based on tension or bend test results is that a metal with very little ductility is not likely to perform in a ductile manner in any other type of mechanical test carried to fracture. However, a metal that displays good ductility in a tensile or bend test may or may not behave in a ductile manner in other types of mechanical tests. In fact, ductile (as determined by tensile and bend tests) metals have been known to fracture in service with little or no plastic deformation. This lack of deformation and other aspects of such failures usually indicate that little energy was required to produce the fracture. This general phenomenon prompts metallurgists to speak of the toughness of metal as a property distinct from ductility.[14]

The term *fracture toughness* is defined as the ability of a metal to resist fracture under conditions that are unfavorable to energy absorption in the presence of a notch and to accommodate loads by plastic deformation. Four conditions markedly influence the behavior of a metal. These are the rate of loading, the nature of the load (i.e., whether the imposed stresses are uniaxial or multiaxial), the temperature of the metal, and the presence of a notch.

Many metals can absorb energy and deform plastically under the simple circumstances represented in tension or bend tests (and therefore would be judged ductile); however, a lesser number of these metals exhibit good toughness when tested under conditions of high stress concentration. The toughness displayed by a metal tends to decrease as (1) the rate of loading increases, (2) the applied stresses become multiaxial, and (3) the temperature of the metal is lowered. Weldments in service may easily be exposed to one or more of these conditions. Consequently, concern about the toughness of the weld metal and weld heat-affected zones is warranted.

When ductile metals are employed in the design of engineering structures, including welds, design strength is normally based on an analysis to ensure that the applied stresses are below the design strength. Failures that occur at load levels below the design strength are broadly classified as *brittle failures*. These failures can result from the effects of discontinuities or crack-like defects of critical size in the weld or the base metal that do not greatly alter the nominal stress distribution and are customarily neglected in the design.

When structural grade steel is tested in uniaxial tension, it typically deforms in a ductile manner prior to rupture at the ultimate load. Because the volume of metal must remain constant, any elongation in one direction must be accompanied by contraction in one or both of the other directions. The uniaxial tension test specimen is free to contract in the other direction, resulting in ductile behavior. If the necessary lateral contraction is severely constrained or prevented and the longitudinal stresses are sufficiently large, the same material that exhibits ductile behavior in a simple tension test may fail in a brittle manner.

In structures in which separate elements are joined by welding, the conditions of constraint and stress concentrations are usually very different from those produced by simple uniaxial tension. Substantial material thickness alone may provide sufficient constraint to prevent lateral contractions. Thus, structural details that have proved satisfactory in long usage and service may not necessarily have adequate ductile characteristics if material dimensions are proportionately increased to a large degree.

A complete fracture-safe analysis requires proper attention to the role of discontinuities. For many classes of structures, including ships, bridges, and pressure vessels, experience with specific designs, materials, and fabrication procedures has established a satisfactory correlation between Charpy V-notch test standards

12. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, pp. 147–148.
13. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 148.
14. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 155. For information on fracture toughness, see Chapter 6, "Test Methods for Evaluating Welded Joints," in this volume and Barsom, J. M., and S. T. Rolfe, eds., 1999, *Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics,* 3rd ed., West Conshohocken, Pennsylvania: American Society for Testing and Materials.

for base and weld metals and acceptable service. The challenge is to ensure the soundness and integrity of a new design. Fracture mechanics analyses are employed to guard against the effects of common weld discontinuities. As it is widely recognized that welded joints usually contain some discontinuities, designers using welded joints in their plans are faced with a dilemma. Although they aim to design joints that are entirely free of discontinuities, this goal is not realistic. The practical approach is to place a reasonable limit on those discontinuities that are bound to be present. Consequently, the challenge consists of determining the types and the extent of discontinuities that are acceptable.

While conventional toughness testing procedures cannot directly address this challenge, fracture mechanics tests, where applicable, specifically define the relationship between flaw size transverse to the stress field and fracture stress for a given base metal or weld joint. Thus, these tests permit a direct estimate of acceptable flaw sizes for different geometrical configurations and operating conditions. Fracture mechanics can establish the minimum or critical crack-like flaw size that will initiate unstable crack propagation under tensile stress.

It should be noted, however, that in members subject to cyclic loading or corrosion, or both, cracks might initiate at stress raisers that are considered acceptable discontinuities. These small cracks could grow by stable crack extension with each application of tensile stress until the crack reaches the critical size. For such conditions, information relative to crack growth rate is essential to the establishment of acceptance criteria and continuing inspection frequencies.

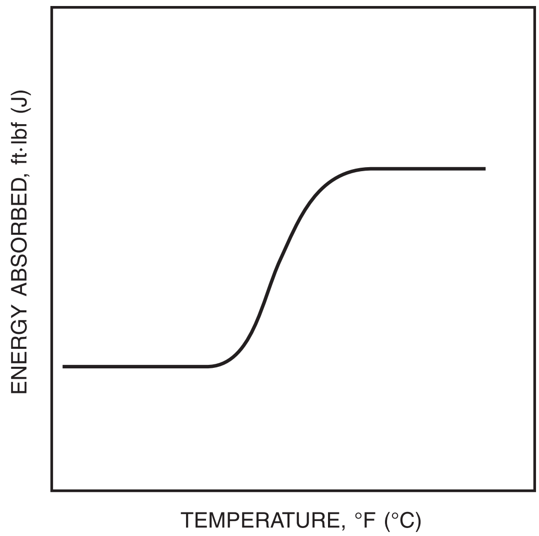


Figure 5.3—Typical Fracture Toughness Transition Curve

Low-Temperature Behavior

As pressure vessels and other welded products are sometimes expected to operate at low (below 32°F [0°C]) temperatures, weldment designers must consider the properties exhibited by metals at these low temperatures. Very low temperatures are involved in cryogenic service, which entails the storage and use of liquefied industrial gases such as oxygen and nitrogen. Lowering the temperature of a metal profoundly affects its fracture characteristics, particularly if the metal possesses a body-centered-cubic crystalline structure (carbon steel, for example).[15]

Strength, ductility, and other properties change in all metals and alloys as the temperature decreases. The modulus of elasticity rises, for instance. As a rule, the tensile and yield strengths of all metals and alloys increase as the temperature is lowered.

Though the ductility of most metals and alloys tends to decrease as the temperature is lowered, some metals and alloys retain considerable ductility at very low temperatures. As discussed in the previous section, fracture toughness is typically a function of temperature. Figure 5.3 presents a transition curve that shows this relationship. At higher and lower temperatures, the fracture toughness is fairly constant. However, between these two plateaus, the fracture toughness decreases as the temperature decreases. This is known as the *ductile-to-brittle transition*. The suitability of metals for low temperature service is judged by testing.

The principal factors that determine the low-temperature behavior of a metal during mechanical testing are (1) crystal structure, (2) chemical composition, (3) the size and shape of the test specimen, (4) the conditions of manufacture and heat treatment, and (5) the rate of loading.

The most common specimen used for low-temperature testing is the Charpy V-notch impact specimen. The Charpy V-notch impact strengths for five common metals are listed in Table 5.3.

Iron and steel suffer a considerable reduction in impact strength at low temperatures. The addition of alloying elements to steel, especially nickel and manganese, can substantially improve fracture toughness at low temperatures, while increased carbon and phosphorus can greatly decrease low-temperature fracture toughness.

15. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, pp. 218–219.

Table 5.3
Typical Notch-Bar Impact Strengths of Metals Tested at Low Temperatures

	Charpy V-Notch Impact Strength, ft · lb (J)									
	Aluminum*		Copper*		Nickel*		Iron†		Titanium‡	
Temperature, °F (°C)	ft lb	J	ft lb	J	ft lb	J	ft lb	J	ft lb	J
75 (room temperature) (25)	20	27	40	54	90	122	75	102	15	20
0 (–18)	20	27	42	57	92	125	30	41	13	18
–100 (–73)	22	30	44	60	93	126	2	3	11	15
–200 (–129)	24	33	46	63	94	128	1	1	9	12
–320 (–320)	27	37	50	68	95	129	1	1	7	10

*Face-centered-cubic crystal structure.
† Body-centered-cubic crystal structure.
‡ Hexagonal close-packed crystal structure.

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, Table 3.6.

Elevated-Temperature Behavior

The performance of a metal in service at an elevated temperature (i.e., 75°F [25°C] to 500°F [260°C]) is governed by other factors in addition to strength and ductility. Time becomes a factor because at high temperatures metals undergo the phenomenon known as *creep,* defined as "deformation with time at service temperature."[16] In other words, the section under stress continues to deform even if the load is maintained constant. The rate at which a metal creeps increases rapidly with increasing temperature and increasing load. Thus, the time over which a metal under load deforms too much to be usable can vary from many years at a slightly elevated temperature to a few minutes at a temperature near the melting point.[17]

The creep rates of metals and alloys differ considerably. If the temperature and stress are sufficiently high, the metal will creep until rupture occurs. The term *creep rupture* is used to identify the mechanics of deformation and the failure of metals under stress at elevated temperatures.

PHYSICAL PROPERTIES

The physical properties of metals constitute an important aspect of the weldability of metals. Welding engineers must be cognizant of the fact that the success of a particular joining operation may depend on one or more physical properties. The constants provided for metals and alloys are satisfactory for most engineering purposes.[18]

Only those physical properties that require consideration in the fields of weldment design and fabrication of a weldment are discussed here.[19] These include thermal conductivity, melting temperature, thermal expansion and contraction, and electrical conductivity.

Thermal Conductivity

The rate at which heat is transmitted through a material by conduction is referred to as *thermal conductivity* or *thermal transmittance*. Metals are better heat conductors than nonmetals, and metals with high electrical conductivity generally have high thermal conductivity.

Metals differ considerably in their thermal conductivities. Copper and aluminum are excellent conductors, which makes these metals difficult to weld using a relatively low-temperature heat source such as an oxyacetylene flame. Conversely, the high conductivity of copper makes it a good heat sink when employed as a hold-down or backing bar.

Melting Temperature

As a rule, the higher the melting point is, the greater the amount of heat needed to effect melting. Thus, the temperature of the heat source in welding must be well

16. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 242.
17. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 244.
18. Linnert, G. E., 1994, *Welding Metallurgy,* 4th ed., Miami: American Welding Society, p. 258.
19. The physical properties of metals are discussed in greater detail in Chapter 2 of this volume.

above the melting point of the metal. In addition, the welding of two metals of dissimilar compositions becomes more challenging as the difference in their melting points become greater.

Thermal Expansion and Contraction

The distortion that results from welding must be considered during weldment design so that the final dimensions of the weldment are acceptable. Most metals increase in volume when heated and decrease in volume when cooled. The term *coefficient of thermal expansion* refers to the unit change in the linear dimensions of a body when its temperature is changed by one degree. Thus, this coefficient serves as an indicator of expansion and contraction in a metal subjected to increasing or decreasing temperature, respectively.

Although engineers are generally concerned with changes in length in metal components, a linear coefficient of thermal expansion is not the only design consideration. A coefficient for volume change is also important. Metals also change in volume when they are heated and cooled during welding. Thus, the greater the increase in volume and localized upsetting during heating, the more pronounced the distortion from welding.

Electrical Conductivity

Metals are relatively good conductors of electricity. However, increasing the temperature of a metal interferes with the electron flow, resulting in a decrease in electrical conductivity. Adding alloying elements to a metal and cold working also decrease conductivity. Electrical conductivity is an important variable, particularly in the resistance welding processes, inasmuch as the electrical flow is imperative to weld soundness.

CORROSION PROPERTIES

The corrosion properties of a metal determine its mode and rate of deterioration by means of a chemical or electrochemical reaction with the surrounding environment. As metals and alloys differ greatly in their corrosion resistance, this behavior merits consideration in planning and fabricating a weldment for a particular service. Designers must therefore be familiar with the behavior of welded joints under corrosive conditions.[20]

Weld joints often display corrosion properties that differ from the remainder of the weldment. Differences may be observed between the weld metal and the base metal and sometimes between the heat-affected zone and the unaffected base metal. The surface effects produced by welding—heat tint formation and oxidation, for example—are also important factors in the corrosion behavior of the weld metal.

Welds made between dissimilar metals or with dissimilar filler metals may be subject to electrochemical corrosion. Therefore, appropriate protective coatings are required to avoid corrosion in sensitive environments.

WELDMENT DESIGN PROGRAM

A weldment design program begins with the recognition of a need. This need may be for an improvement in an existing machine or for the building of an entirely new product or structure using advanced design and fabrication techniques. In any case, many factors must be taken into account before a design is finalized. These considerations involve numerous questions and considerable research into the various areas of engineering, production, and marketing.

ANALYSIS OF EXISTING DESIGNS

When an entirely new machine or structure is to be designed, information should be obtained about similar products, including those marketed by other manufacturers or builders. If a new design is to replace an existing design, the strengths and weaknesses of the existing design should be determined. The following factors should be considered in identifying the strengths and weaknesses of existing designs:

1. Performance history of the existing products;
2. Features that should be retained, discarded, or added;
3. Any suggestions for improvements that have been made; and
4. Opinions of customers and the sales force about the existing products.

DETERMINATION OF LOAD CONDITIONS

The service conditions and requirements of a weldment that might cause the overloading of a weldment should be ascertained. As a starting point for the calculation of loads, the following guidelines may be useful:

1. Determine the torque on a shaft or revolving part from the motor horsepower and speed;

20. The types of corrosion and the corrosion testing of welds are discussed in Chapter 6 of this volume.

2. Calculate the forces on members caused by the dead weight of the parts;
3. Determine the maximum load on members of a crane hoist, shovel, lift truck, or similar material handling equipment from the load required to tilt the machine;
4. Consider the force required to shear a critical pin as an indication of maximum loading on a member; and
5. Determine the desired service life and the frequency of loading (for example, designing for fatigue at lesser loads may be more critical than designing for maximum strength to resist infrequently applied maximum loads).

In the absence of a satisfactory starting point, the designer should plan for an assumed load and adjust the design based on experience and testing.

MAJOR DESIGN FACTORS

In developing a design, designers should consider the manner in which decisions affect production operations, manufacturing costs, product performance, appearance, and customer acceptance. Many factors that are seemingly far removed from engineering considerations can become major design factors. Some of these, along with other relevant rules, are highlighted below:

1. The design should satisfy strength and stiffness requirements, but overdesigning not only constitutes a poor engineering practice but also wastes materials and labor and increases production and shipping costs;
2. Safety factors should be realistic;
3. As an attractive appearance may be necessary in areas exposed to view, the drawing or specifications should indicate those welds that must be ground or otherwise conditioned to enhance appearance;
4. Deep, symmetrical sections should be used to minimize distortion;
5. Welding the ends of beams rigidly to supports may increase strength and stiffness;
6. Rigidity may be provided by welded stiffeners, precluding the need to increase material thickness and weight;
7. Tubular sections or diagonal bracing should be used for torsion loading, as a closed tubular section is significantly more effective in resisting torsion than an open section of similar weight and proportions;
8. Standard rolled sections, rather than special built-up sections, should be used for economy and availability when they satisfy the need;
9. Accessibility for maintenance must be considered during the design phase; and
10. Standard, commercially available components such as index tables, way units, heads, and columns should be specified when they would serve the purpose.

DESIGNING THE WELDMENT

Flexibility is one of the advantages of welded design, resulting in many opportunities for savings. The following are general suggestions for effective design:

1. Design for ease of material handling, inexpensive tooling, and accessibility of the joints for reliable welding;
2. Check with the shop for ideas that can contribute to cost savings;
3. Establish realistic tolerances based on end use and suitability for service, as excessively close tolerances serve no useful purpose and increase costs; and
4. Minimize the number of pieces to reduce assembly time and the amount of welding.

Workpiece Preparation

Thermal cutting, shearing, sawing, blanking, nibbling, and machining are methods used to cut blanks from stock material. The selection of the appropriate method depends on the available material and equipment and the relative costs. The quality of edges needed for good fitup and the type of edge preparation for groove welds must be kept in mind. The following points should also be considered when preparing material for welding:

1. Dimensioning of a blank may require a stock allowance for subsequent edge preparation,
2. The detail of the welded joints must be considered when laying out a blank with the intent to cut and prepare the edge for welding simultaneously,
3. Weld metal costs can be reduced for thick plate by specifying J- or U-groove preparations, and
4. Air carbon arc gouging, oxygen gouging, or chipping should be contemplated for back weld preparation.

Forming

The forming of parts can sometimes reduce the cost of a weldment by avoiding joints and machining operations. The selection of a forming method is based on the composition of the base metal, thickness, overall dimensions, production volume, tolerances, and cost. The following suggestions may facilitate the decision-making process:

1. Corners can be created by bending or forming rather than by welding two pieces together,
2. Flanges can be bent on the plate rather than welding flanges to it,
3. A casting or forging can be used in place of a complex weldment to simplify the design and reduce manufacturing costs, and
4. A surfacing weld instead of an expensive alloy component can be used on an inexpensive component to provide wear resistance or other properties.

Cold forming reduces the ductility and increases the yield strength of metals. Heat treating the metal to restore ductility may increase or decrease the strength, depending on the alloy type. The heat produced by arc welding on a cold-formed material may also affect the mechanical properties of the base metal. The mechanical properties of the heat-affected zone of cold-formed materials may be reduced by the heat of welding. Generally, the relevant standard provides the maximum cold-forming allowances and minimum strength properties of cold-formed weldments. For instance, Section VIII of the *1998 Boiler and Pressure Vessel Code* requires that under certain circumstances cold forming that results in extreme fiber elongation (over 5%) in carbon, low-alloy, and heat-treated steel plates must be stress relieved.[21] It should be noted that welding in close proximity to material that has been strained 5% or more results in material with negligible notch toughness.

Weld Joint Design

Weld joint design should be selected primarily on the basis of load requirements. However, variables in design and layout can substantially affect costs. The following guidelines generally apply:

1. The joint design that requires the least amount of weld metal should generally be selected;
2. Otherwise, square-groove and partial joint penetration groove welds should be used whenever they satisfy strength and serviceability requirements;
3. Lap joint and fillet welds should be used instead of groove welds unless the lower fatigue resistance of these joints is inadequate to satisfy the service requirements;
4. Double-V- or U-groove welds should be used instead of single-V- or U-groove welds on thick plates to minimize the amount of deposited weld metal and resulting distortion;
5. For corner joints in thick plates in which fillet welds are not adequate, the beveling of the members subject to through-thickness weld shrinkage strains should be considered to reduce the tendency for lamellar tearing; and
6. The assembly and joints should be designed to provide ready accessibility for welding.

Size and Amount of Weld

Overdesign is a common error, as is overwelding in production. The control of weld size begins with design, but it must be maintained during the assembly and welding operations. The following are basic guidelines regarding the control of weld size:

1. Adequate but minimum size and length should be specified for the forces to be transferred. Oversized welds may cause excessive distortion and higher residual stress without improving suitability for service; they also contribute to increased costs. The size of a fillet weld is especially important because as the fillet weld size increases, the weld metal cross-sectional area increases in proportion relative to the weld size squared;
2. For equivalent strength, a continuous fillet weld of a given size is usually less costly than a larger-sized intermittent fillet weld. Continuous fillet welds also have fewer weld terminations, which are potential sites of discontinuities;
3. An intermittent fillet weld can be used in place of a continuous fillet weld of minimum size when static load conditions do not require a continuous weld. However, it should be recognized that intermittent fillet welds should have a low allowable stress range when cyclic loading is a design consideration;
4. To derive maximum advantage from automatic welding, it may be better to use one continuous weld rather than intermittent welds;
5. Weld size should not be larger than that required for the strength of the thinner workpiece based on the load;
6. Welding of stiffeners or diaphragms should be limited to that required to prevent out-of-plane distortion of the supported components under maximum loads as well as during shipment and handling; and

21. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, 1998, *1998 Boiler and Pressure Vessel Code*, New York: American Society of Mechanical Engineers (ASME).

7. The amount of welding should be kept to a minimum to limit distortion and internal stresses, thus minimizing the need for and the cost of stress relieving and straightening.

Subassemblies

In visualizing assembly procedures, designers should break the weldment into subassemblies to determine the arrangement that offers the greatest cost savings. Subassemblies offer the following advantages:

1. Two or more subassemblies can be worked on simultaneously;
2. Subassemblies usually provide better access for welding and may permit automatic welding;
3. Distortion in the finished weldment may be easier to control;
4. Large-sized welds may be deposited under lesser restraint in subassemblies, which aids in minimizing residual stresses in the completed weldment;
5. Machining of subassemblies to close tolerances and stress relieving of certain sections can be performed before final assembly, if necessary;
6. Chamber compartments can be tested for leaks and painted before final assembly;
7. In-process inspection and repair is facilitated; and
8. Handling costs tend to be much lower.

WELDING PROCEDURES

Although designers have little control of welding procedures, they can influence which procedures are used in production. The following guidelines can help to ensure the ultimate success of weldment design:

1. Backing bars increase the speed of welding when making the first pass in groove welds;
2. The use of low-hydrogen electrodes and welding processes may eliminate or reduce preheat requirements;
3. If the plates are not too thick, a joint design requiring welding from only one side should be considered to avoid repositioning or overhead welding;
4. A built-up or crown weld is generally unnecessary to obtain a full-strength joint;
5. Joints in thick sections should be welded under conditions of the least restraint, for example, prior to the installation of stiffeners; and
6. Sequencing of fitup, fixturing, and welding is particularly important for box members made of plates because after the completion of welding the correction of distortion is virtually impossible.

LAMINATIONS AND LAMELLAR TEARING

Weldment designers must understand the true significance of the residual stresses that result from the contraction of the cooling weld metal. These contractions result in strains that are in excess of yield level strains if sufficient restraint exists. The shrinkage strains provide the potential for lamellar tearing—the formation of cracks parallel to the direction of rolling in material stressed in the through-thickness direction. Lamellar tears generally initiate from flattened, low-melting-point constituents in steel (e.g., manganese sulfides).

Lamellar tears occur most often during fabrication shortly after the solidification of the weld metal. Because the strains associated with design stresses are so small (limited to less than yield point stress by code) in comparison to the weld shrinkage strains that are responsible for lamellar tearing, service loads do not initiate lamellar tearing. The detail geometry, material thickness, and weld size selected may lead to difficult or virtually impossible fabrication conditions.

In connections in which a member is welded to the outside surface of a main member, the capacity to transmit through-thickness tensile stresses is essential to the proper functioning of the joint. Laminations, which are pre-existing planes of weakness, and lamellar tears may impair this capacity.

Consideration of the phenomenon of lamellar tearing must include design aspects and welding procedures that are consistent with the properties of the base material. In connections in which lamellar tearing might be a concern, the design should provide for maximum component flexibility and minimum weld shrinkage strain.[22]

The following precautions should help to minimize lamellar tearing in highly restrained welded connections:[23]

1. On corner joints, the edge preparation should be on the through-thickness member, when feasible;
2. The size of the weld groove should be kept to a minimum, consistent with the design requirements;
3. Overwelding should be avoided because rather than providing conservative design it may cause the material to weaken;
4. Welds in corner and T-joints should be completed early in the fabrication process, if possible, to minimize restraint in such joints;
5. A predetermined welding sequence should be selected to minimize overall shrinkage in the most highly restrained elements;
6. The lowest-strength weld metal available, consistent with design requirements, should be used

22. For further information, see Section 2 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society.
23. It is assumed that procedures producing low-hydrogen weld metal would be used.

to promote straining in the weld metal rather than in the more sensitive through-thickness direction of the base metal;

7. Buttering with weld metal approximately 3/16 in. (5 mm) thick and extending beyond the limits of the joint prior to fitup has been shown by research testing to provide an area of material less susceptible to lamellar tearing at the location where the most severe strains occur. This technique has proven very effective in reducing the hazard of lamellar tearing; and
8. Specification of a material with improved through-thickness ductility should be considered for critical connections.[24]

In critical joint areas subject to through-thickness direction loading, ultrasonic examination should be conducted to avoid the use of a material containing preexisting laminations and large nonmetallic inclusions. In addition, no sooner than 48 hours after the completion of welding, designers should specify postwelding ultrasonic inspection of those specific highly restrained connections that could be subject to lamellar tearing and are critical to the structural integrity. They must also consider whether minor weld flaws or base metal imperfections can be left unrepaired without jeopardizing structural integrity.

Gouging and repair welding add additional cycles of weld shrinkage to the connection and may result in the extension of existing flaws or the generation of new flaws by lamellar tearing.

CLEANING AND INSPECTION

Design specifications can affect cleaning and inspection costs. The safety requirements of the weldment determine the type and amount of inspection required. The timeliness of inspection is of paramount importance in order to maintain the orderly flow of work and correct deficiencies without interfering with subsequent operations. For example, as-welded joints that have uniform appearance are acceptable for many applications. Therefore, the surface of a weld need not be ground smooth or flush unless required for another reason inasmuch as the smoothing of a weld is an additional operation.

Undesirable overwelding should be noted during inspection because it can be costly and it contributes to distortion. Corrective action should be directed at work in progress rather than at completed weldments. The type of nondestructive inspection to be used on weldments must be capable of detecting the types and sizes of weld discontinuities that are to be evaluated for acceptability.[25]

WELDED DESIGN CONSIDERATIONS

The performance of any member of a structure depends on the properties of the material and the characteristics of the section. If a design is based on the efficient use of these properties, the weldment should function well and conserve materials. Engineers assigned to design welded members must possess the knowledge to select the most efficient structural section and determine the required dimensions. They must also know when to use stiffeners and how to size and place them when used.

The mathematical equations utilized to calculate forces and their effects on sections and to determine the sections needed to resist such forces appear quite forbidding to the novice. With the proper approach, however, it is possible to simplify the design analysis and the application of these equations. In fact, as is explained below, it is often possible to make correct design decisions merely by examining one or two factors in an equation, precluding tedious calculations. As a whole, the mathematics used in design for welding is no more complex than that used in other engineering fields.

APPROACH TO WELD REDESIGN

From the standpoint of performance and ultimate production economics, the redesign of the machine or structure as a whole is preferable. The designer is then unrestricted by the previous design and may be able to reduce the number of pieces, the amount of material used, and the labor for assembly. A better, lower-cost product is realized immediately. When the adjustment to changes in production procedures is complete, the company is in a position to benefit more fully from welded design technology.

However, considerations other than the engineer's wishes may prevail. Available capital and personnel considerations often limit a company's capabilities when changing to welded design. For example, when a machine is to be converted from a casting to a welded design, management may favor the redesign of one or more components over the use of weldments and the conversion of the design over a period of years to an all-

24. Improved quality steel does not eliminate weld shrinkage and does not necessarily prevent lamellar tearing in highly restrained joints. Thus, this material should not be specified in the absence of comprehensive design and fabrication considerations.

25. For further information, refer to the Chapter 14, "Inspection and Nondestructive Examination," in this volume.

welded product. Gradual conversion avoids the obsolescence of facilities and skills and limits the requirement for new equipment. Supplementing these considerations is the need to maintain a smooth production flow and to test the production and market value of the conversion as it is made step by step.

REDESIGN VERSUS NEW DESIGN

A redesign of a product may be based on the previous design or solely on loading considerations. Following a previous design has the advantages of offering a “safe” starting point if the old design is known to have performed satisfactorily. This approach has disadvantages, however, in that it stifles creative thinking with respect to the development of an entirely new concept to solve the basic problem. Little demand is made on the ingenuity of the designer when the welded design is modeled on the previous product.

A design based on the loading requires designers to analyze what is needed and propose configurations and materials that best satisfy the identified needs. They must know or ascertain the type and amount of load, the values for stress allowables in a strength design, or the deflection allowables in a stiffness design.

STRUCTURAL SAFETY CONSIDERATIONS

The production of a safe welded structure depends upon a combination of proficient design practices, skilled fabrication, and sound construction methods. In design, the selection of a safety factor and the appropriate analytical procedures requires experience and sound engineering judgement. Deterioration as a result of corrosion or other service conditions during the life of the structure, variations in material properties, potential imperfections in materials and welded joints, and many other factors also need consideration.

A rational approach to structural safety is a statistical evaluation of the random nature of all the variables that determine the strength of a structure as well as the variables that may cause it to fail. From these data, the probability of failure can be evaluated and the probability of occurrence kept at a safe level for the application, taking into considering the risk of injury, death, property damage, and unsatisfactory service performance. The choice of materials and safe stress levels in members may not produce the most economical structure. However, safety must take precedence over cost savings whenever a question of which should govern arises.

When designers attempt a new design or structural concept, great skill and care as well as detailed stress analyses are required. Laboratory tests of models or sections of prototype structures should be used to verify new designs.

DESIGNING FOR STRENGTH AND STIFFNESS

A design may require strength only or strength and stiffness to support the load. All designs must have sufficient strength to prevent the members from failing by fracture or yielding when subjected to normal operating loads or reasonable overloads. Strength designs are common in road machinery, farm implements, motor brackets, and various types of structures. If a weldment design is based on calculated loading, design equations for strength are used to dimension the members. Tables of equivalent sections or nomographs can be used to determine required dimensions for strength and stiffness.

In weldments such as machine tools, stiffness as well as strength is important because excessive deflection under load results in a lack of precision in the product. A design based on stiffness also requires the use of design equations for sizing members.

Some parts of a weldment serve their design function without being subjected to loads much greater than their own weight, or dead loads. Typical examples of such members are fenders, dust shields, safety guards, cover plates for access holes, and enclosures included for aesthetic purposes. Only casual attention to strength and stiffness is required in sizing such members.

DESIGN EQUATIONS

The design equations for strength and stiffness always contain terms representing the load, the member, the stress, and the strain or deformation. If any two of the first three terms are known, the others can be calculated. All problems of design thus reduce into one of the following:

1. Determination of the internal stress or the deformation caused by an external load on a given member,
2. Determination of the external load that may be placed on a given member for any given strength or deformation, or
3. Selection of a member to carry a given load without exceeding a specified strength or deformation.

A force causes a reaction such as tension, compression, bending, torsion, or shear stress in the member. The result is a strain measured by means of the relative displacements in the member. These include elongation, contraction, deflection, or angular twist. A useful member must be designed to carry a certain type of load within an allowable stress or deformation. In designing within the allowable limits, designers should select the most efficient material section size and section shape.

The properties of the material and those of the section determine the ability of a member to carry a given load.

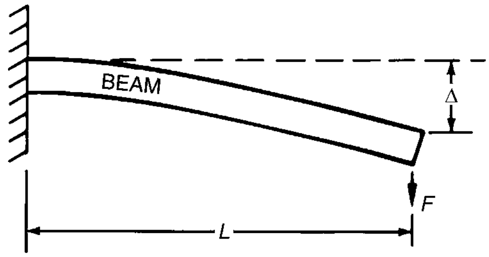
The common design equations that have been developed for various conditions and member types are too numerous for inclusion here. However, several of these equations are presented below to illustrate specific design problems.[26]

The application of design equations can be illustrated by the problem of obtaining adequate stiffness in a cantilever beam. The amount of vertical deflection at the end of the beam under a concentrated load at the end, illustrated in Figure 5.4, can be determined using the following equation for deflection:

$$\Delta = \frac{FL^3}{3EI} \tag{5.2}$$

where

Δ = Deflection, in. (mm);
F = Concentrated load, lbf (N);
L = Length, in. (mm);
E = Modulus of elasticity, psi (MPa); and
I = Moment of inertia, in.^{4} (mm^4).



Key:
Δ = Deflection, in. (mm)
F = Concentrated load, lbf (N)
L = Length, in. (mm)

Figure 5.4—Deflection (Δ) of a Cantilever Beam Under a Concentrated Load, *F*

It is normally desirable to have the least amount of deflection. Therefore, the modulus of elasticity and moment of inertia values should be as large as possible. The commonly used structural metal that has the highest modulus of elasticity is steel, with a value of approximately 30×10^6 psi (200,000 MPa).

The other factor is the moment of inertia of a cross section. The moment of inertia of a member is a function of the geometry of the member. The beam must have a cross section with a moment of inertia about the horizontal axis large enough to limit the deflection to a permissible value. A section with an adequate in-plane moment of inertia will satisfy the vertical deflection requirement, whatever the shape of the section may be. However, the out-of-plane stability of the beam may also need consideration, especially if the forces are transverse to the principal axis or if torsion is involved. A decision must then be made as to which shape should be used for the best design at the lowest cost.

Types of Loading

The five basic types of loading are tension, compression, bending, shear, and torsion. When one or more types of loading are applied to a member, they induce stress in addition to any residual stresses that are present.

The applied load results in stress within the member, and the magnitude of the strain is governed by the modulus of elasticity of the metal. Some deformation always takes place in a member when the load is applied because the associated stress inevitably causes strain.

Tension. Pure tensile loading is generally the simplest type of loading from a design and analysis perspective. Axial tensile loads cause axial strains and elongation. In the case of tensile loading, the principal design requirement is an adequate gross and net cross-sectional area to carry the load.

Compression. A compressive load may require appropriate design provisions to prevent buckling. Few compression members fail by crushing or by exceeding the ultimate compressive strength of the material. If a straight compression member such as the column represented in Figure 5.5(A) is loaded through its center of gravity, the resulting stresses are simple axial compressive stresses. If the member is a slender column, it will start to bow laterally as a result of small imperfections and accidental eccentricity of loading. This movement is shown in Figure 5.5(B). As a result of bowing, the central portion of the column becomes increasingly eccentric to the axis of the force and causes a bending moment on the column, as shown in Figure 5.5(C).

Under a steady load, the column will remain stable under the combined effect of the axial stress and the bending moment. However, with increasing load and the associated curvature, depicted in Figure 5.5(D), a

26. The properties of sections for standard structural shapes are given in American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design,* Vols. 1 and 2, Chicago: American Institute of Steel Construction; and the Aluminum Association, 1994, *Aluminum Design Manual: Specifications and Guidelines for Aluminum Structures,* Washington, D.C.: Aluminum Association.

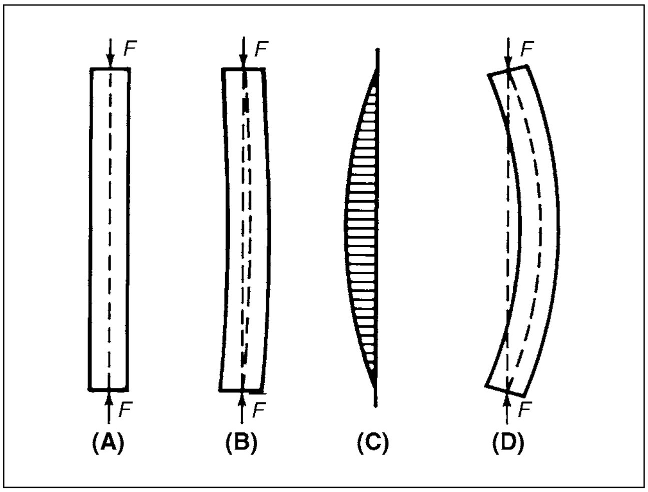


Figure 5.5—Schematic Representation of Compressive Load Force (*F*): (A) Straight Column Under Compressive Load; (B) Column Defects Laterally with Increasing Load; (C) Bending Moment Diagram; and (D) Increased Deflection with Higher Loading

critical point will be reached at which the column will buckle and fail. The presence of residual stresses developed during manufacturing may also reduce the failure load. As a column deflects under load, a bending moment can develop in restrained end connections.

Two properties of a column are important for the calculation of compressive strength—the cross-sectional area, A, and the radius of gyration, r, which is the distance from the neutral axis of the section to an imaginary line in the cross section about which the entire area of the section could be concentrated and still have the same moment of inertia about the neutral axis of the section. The area is multiplied by the critical buckling stress, σ_{cr}, to arrive at the compressive load that the column can support in the absence of buckling. The radius of gyration indicates, to a certain extent, the column's ability to resist buckling. The equation for the radius of gyration is as follows:

$$r = \sqrt{\frac{I}{A}} \tag{5.3}$$

where

r = Radius of gyration, in. (mm);
I = Moment of inertia about the neutral axis, in.^{4} (mm^4); and
A = Cross-sectional area of the member, in.^{2} (mm^2).

Inasmuch as the worst condition is always of concern in design work, it is necessary to use the smallest radius of gyration relative to the unbraced length. Thus, an overloaded unbraced wide-flange column section will always buckle, as shown in Figure 5.5(D). However, if the column is braced at the mid-length to prevent buckling, the column could buckle toward a flange. The critical slenderness ratio of a column is the larger of ratios L_x/r_x or L_y/r_y, where L_x and L_y are the distances between braced points, and r_x and r_y are the radii of gyration about the x and y axis, respectively.

The design of a long compression member is carried out by trial and error. A trial section is selected, and the cross-sectional area and the least radius of gyration are determined. A suitable column table[27] is used to provide the critical buckling stress, σ_{cr}, for the column slenderness ratio, KL/r. This stress is then multiplied by the cross-sectional area, A, to find the buckling strength of the column and, when a suitable safety or resistance factor is chosen, the design load the column can carry. If this value is less than the load to be applied, the design must be changed to incorporate a larger section and calculated again. Table 5.4 presents the AISC load and resistance factor design (LRFD) column equations.

Table 5.4
Critical Axial Compressive Stress Equations

For $\lambda_c \le 1.5$:

$$\sigma_{cr} = \left(0.658^{\lambda_c^2}\right)\sigma_y \tag{1}$$

For $\lambda_c > 1.5$:

$$\sigma_{cr} = \left(\frac{0.877}{\lambda_c^2}\right)\sigma_y \tag{2}$$

where

λ_c = Column slenderness parameter, which equals

$$\left(\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}}\right)\frac{KL}{r};$$

σ_{cr} = Critical compressive stress, ksi (MPa);
K = Effective length factor (ratio of the length of an equivalent pinned ended member to the length of the actual member);
L = Unbraced length of the member, in. (mm);
r = Radius of gyration, in. (mm);
E = Modulus of elasticity, ksi (MPa); and
σ_y = Yield strength, ksi (MPa).

Source: American Institute of Steel Construction (AISC), 1993, *LRFD Specification for Structural Steel Buildings*, Chicago: American Institute of Steel Construction, Section E2.

27. See American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction.

Bending. Figure 5.6 illustrates the bending of a member under uniform loading. Loads may also be nonuniform or concentrated at specific locations on the beam. When a member is loaded in bending within the elastic range, the bending stresses total zero along the neutral axis and increase linearly to a maximum value at the outer fibers.

The bending stress at any distance from the neutral axis in the cross section of a straight beam is shown in Figure 5.7.

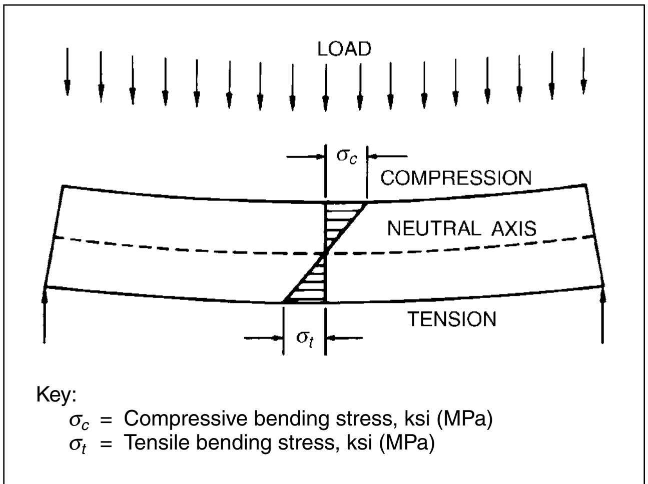


Figure 5.6—Bending of a Beam with Uniform Loading

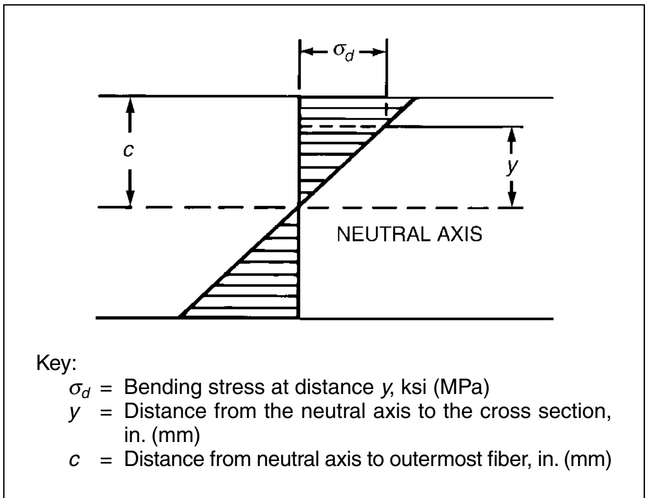


Figure 5.7—Bending Stress (σ_d) at Any Point (*y*) in the Cross Section of a Straight Beam Elastically Loaded

The bending stress can be found with the following expression:

$$\sigma = \frac{My}{I} \tag{5.4}$$

where

σ = Bending stress (tension or compression), ksi (MPa);
M = Bending moment at the point of interest, kip inches (kips in.) (kilonewton millimeters [kN mm]);
y = Distance from the neutral axis of bending to a specific distance, "y," in. (mm); and
I = Moment of inertia about the neutral axis of bending, in.^{4} (mm^4).

In most cases, the maximum bending stress is of greatest interest. In this case, the equation becomes:

$$\sigma = \frac{Mc}{I} = \frac{M}{S} \tag{5.5}$$

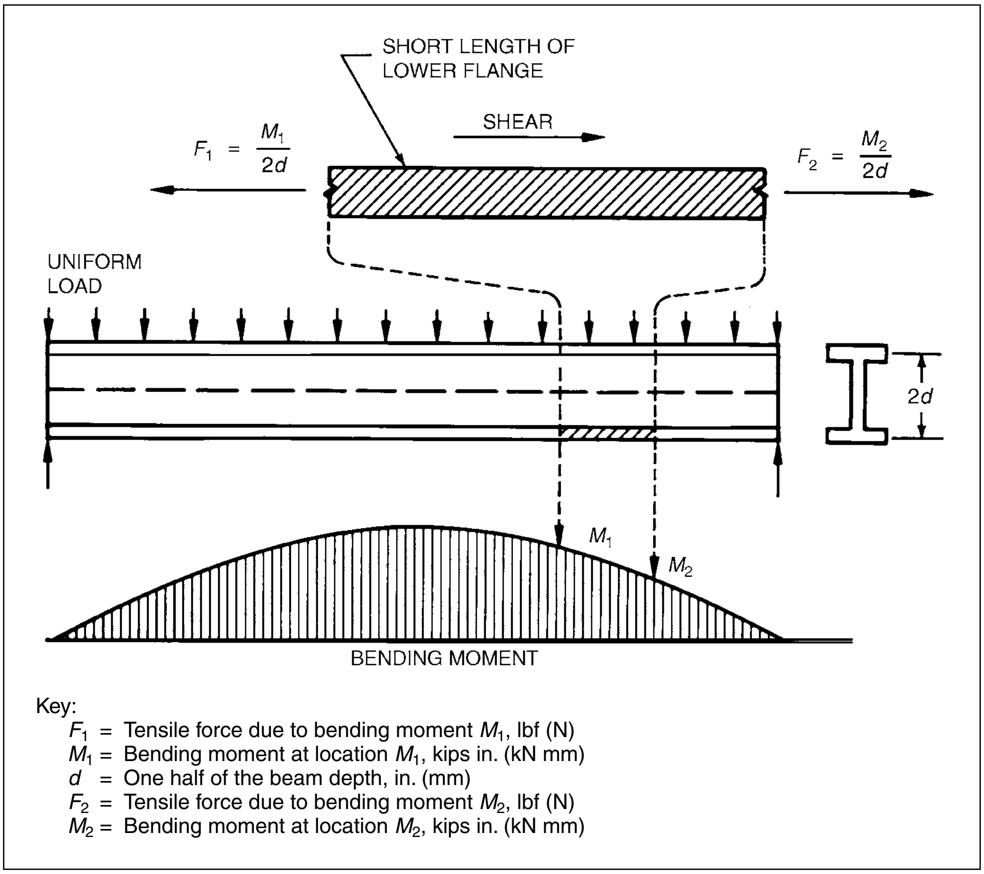
where

σ = Bending stress (tension or compression), ksi (MPa);
M = Bending moment at the point of interest, kips in. (kN mm);
c = Distance from the neutral axis of bending to the outermost fibers, in. (mm); and
S = Section modulus (I/c), in.^{3} (mm^3).

As the bending moment decreases along the length of a simply supported beam toward the ends, the bending stresses (tension and compression) in the beam also decrease. If a beam has the shape of an I-section, the bending stress in the flange decreases as the end of the beam is approached. If a short length of the tension flange within the beam is considered, a difference exists between tensile forces[28] F_1 and F_2 at the two locations in the flange, as shown in Figure 5.8.

The decrease in the tensile force in the flange results in a corresponding shearing force between the flange and the web. This shearing force must be transmitted by the fillet welds that join the two together. The same reaction takes place in the upper flange, which is in compression. The change in tensile force in the lower flange transfers as shear through the web to the upper flange and is equal to the change in compression in that flange.

28. The tensile force, F, is the product of the tensile stress, σ, and the flange cross-sectional area, A.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-10.

Figure 5.8—Approximate Tensile Forces (F_1 and F_2) on a Section of the Lower Flange of a Loaded Beam

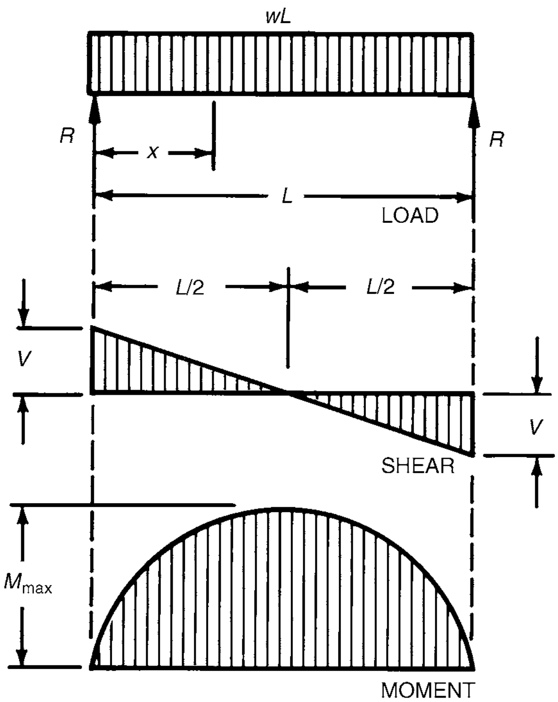
A common bending problem in machinery design involves the deflection of beams. The beam equations found in many engineering handbooks are useful for quick approximations of deflections of common types of beams in which the span is large compared to the beam depth. An example of a typical beam and applicable equations are presented in Figure 5.9.

Beams that are supported or loaded in different ways have other applicable design equations. To meet stiffness requirements, the beam should have as large a moment of inertia as practical.

Information concerning the design of a compression member or column may also apply to the compression flange of a beam. The lateral buckling resistance of the compression flange must also be considered. It should have adequate width and thickness to resist local buckling. Moreover, it should be properly supported to prevent twisting or lateral movement and subjected to compressive stresses within allowable limits.

Shear. Shear forces in the web of a beam under load are illustrated in Figure 5.10. The forces are both horizontal and vertical. They create diagonal tensile and diagonal compressive stresses.

The shear capacity of a member of either an I- or a box-beam cross section is dependent upon the slenderness proportion of the web or webs. For virtually all hot-rolled beams and welded beams of similar proportions in which the web slenderness ratio *(h/t)* is less than 260, the vertical shear load is resisted by pure beam shear, and lateral buckling does not occur. This is true for a level of loading well above that at which unacceptable deflections will develop. Thus, the design is configured to maintain the shear stress on the gross area of



Equations:

Reaction force (R):	$R = V_{max} = \dfrac{wL}{2}$	(1)
Shear force (V_x):	$V_x = w\left(\dfrac{L}{2} - x\right)$	(2)
Maximum moment, M, at center (M_{max}):	$M_{max} = \dfrac{wL^2}{8}$	(3)
Moment at any point (M_x):	$M_x = \dfrac{wx}{2}(L - x)$	(4)
Deflection, Δ, at center (Δ_{max}):	$\Delta_{max} = \dfrac{5wL^4}{384EI}$	(5)
Deflection at any point (Δ_x):	$\Delta_x = \dfrac{wx}{24EI}\left(L^3 - 2Lx^2 + x^3\right)$	(6)
Slope at the ends of the beam (θ):	$\theta = \dfrac{wL^3}{24EI}$	(7)

Key:
- w = Equally distributed force on beam, kips (kN)
- R = End reaction, kips (kN)
- x = Distance from the reaction to a specific location, in. (mm)
- L = Span length, in. (mm)
- V = Shear force, kips (kN)
- M_{max} = Maximum moment, kips in. (kN mm)

Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-15.

Figure 5.9—Equations for a Simply Supported Beam with a Uniformly Distributed Load on the Beam Span

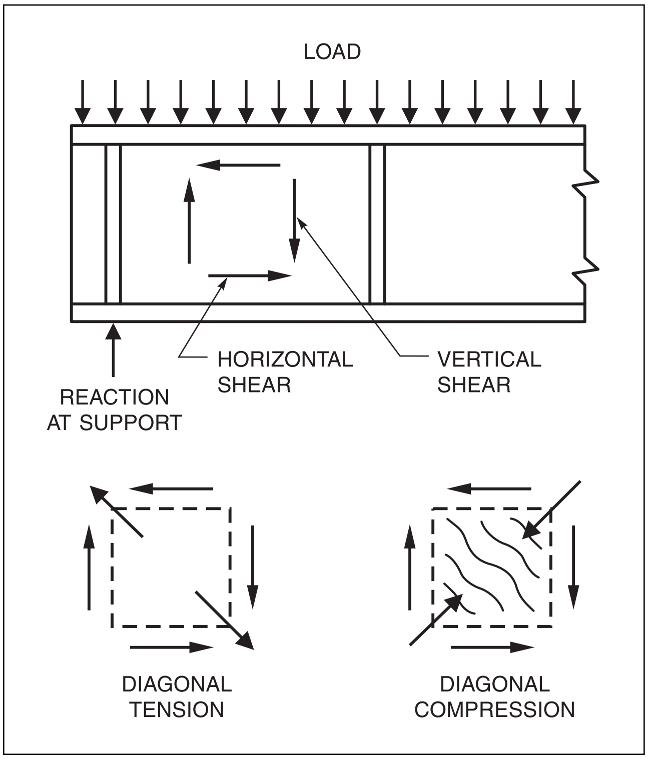
the web below the nominal shear strength of 0.6 σ_y by a factor of safety or a resistance factor to prevent yielding in shear.

In plate girders with slender webs, shear is resisted by plane beam shear up to a level of stress that will cause shear buckling. However, webs subject to shear stress that are stiffened by transverse stiffeners have considerable postbuckling strength. Current design specifications take this strength into account. After buckling occurs, the web resists larger shear loads with a combination of beam shear and diagonal tension in the panels between stiffeners. If the length-to-depth ratio of the panel is approximately 3 or more, the direction of the diagonal tension becomes too near to the horizontal for it to be effective in providing significant postbuckling strength, and the shear strength is limited to beam shear strength.

The onset of diagonal compression buckling in a web panel has negligible structural significance. With properly proportioned transverse stiffeners, the web continues to resist higher levels of shear loading up to the point at which diagonal tension yielding occurs.[29]

Several practical considerations independent of maximum strength may govern a design. For architectural reasons, especially in exposed fascia girders, the waviness of the web caused by controlled compression buckles may be deemed unsightly. In plate girders subject to cyclic loading to a level that would initiate web shear buckling, each application of the critical load causes an "oil canning" or "breathing" action of the web panels. This action causes out-of-plane bending stresses at the toes of web-to-flange fillet welds and the stiffener welds. These cyclic stresses eventually initiate fatigue cracking. For these cases, web stresses should be limited

29. Design criteria to achieve full maximum strength from beam shear and tension field action of the plate and box girder webs may be found in Volume I, Section 6, Chapter G of American Institute of Steel Construction (AISC), 1989, *Manual of Steel Construction: Allowable Stress Design,* Vols. 1 and 2, Chicago: American Institute of Steel Construction.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-11.

Figure 5.10—Shear Forces in the Web of a Beam Under Uniform Load

to the beam shear strength values that preclude shear buckling.

In the case of a beam fabricated by welding, the shear load per unit of length on the welds joining the flanges of the beam to the web can be calculated by means of the following equation:

$$v_s = \frac{Vay}{In} \tag{5.6}$$

where

v_s = Shear load per unit length of weld, kip/in. (kN/mm);
V = External shear force on the member at this location, kip (kN);
a = Cross-sectional area of the flange, in.^{2} (mm^2);
y = Distance between the center of gravity of the flange and the neutral axis of bending of the whole section, in. (mm);
I = Moment of inertia of the whole section about the neutral axis of bending, in.^{4} (mm^4); and
n = Number of welds used to attach the web to the flange.

The required weld size can then be determined from the value of v_s.

Torsion. Torsion creates greater design challenges for bases and frames than for other machine members. A machine with a rotating unit may subject the base to torsional loading. This is evidenced by the lifting of one corner of the base if the base is not anchored to the floor.

If torsion is a problem, closed tubular sections or diagonal bracing should be used, as shown in Figure 5.11. Closed tubular sections are as much as 1000 times better at resisting torsion than comparable open sections. Closed members can easily be made from channel or I-sections by intermittently welding flat plates to the toes of the rolled sections. The torsion effect on the perimeter of an existing frame may be eliminated or the frame may be stiffened for torsion by adding cross bracing. Torsion problems in structures can be avoided by the judicious arrangement of members to transmit loads by direct stresses or bending moments.

Torsional Resistance. The torsional resistance of a flat strip or open section (I-beam or channel) is very low. The torsional resistance of a solid rectangular section having a width of several times the thickness may be approximated by the following expression:[30]

$$R = \frac{bt^3}{3} \tag{5.7}$$

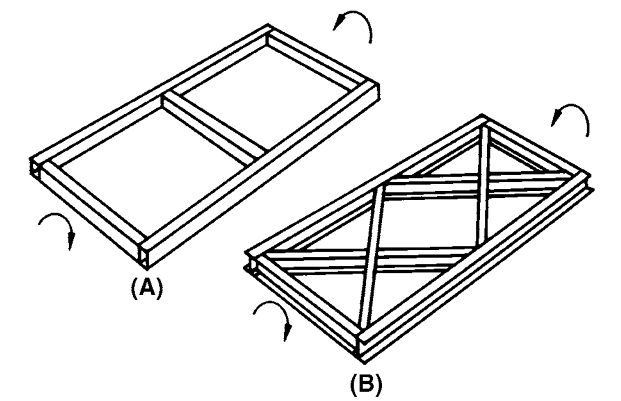
where

R = Torsional resistance, in.^{4} (mm^4);
b = Width of the section, in. (mm); and
t = Thickness of the section, in. (mm).

The unit angular twist, θ, is equal to the total angular twist divided by the length, L, of the member. The total angular twist (rotation) of a member can be estimated by the following equation:

$$\theta = \frac{TL}{GR} \tag{5.8}$$

30. Serberg, P. A., and C. J. Carter, 1996, *Torsional Analysis of Structural Steel Members,* Chicago: American Institute of Steel Construction.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-13.

Figure 5.11—Application of (A) Closed Tubular Sections or (B) Open Structures with Diagonal Bracing to Resist Torsion

where

θ = Angle of twist, radians;
T = Torque, kips in. (kN mm);
L = Length of the member, in. (mm);
G = Modulus of elasticity in shear, ksi (MPa);
R = Torsional resistance, in.^{4} (mm^4).

The torsional resistance of an open structural member such as an I-beam or a channel is approximately equal to the sum of the torsional resistances of the individual flat sections into which the member can be divided. This is illustrated in Table 5.5, which lists the actual and calculated angle of twist of a flat strip and an I-shape made up of three of the flat strips. The applied torque is the same for both sections.

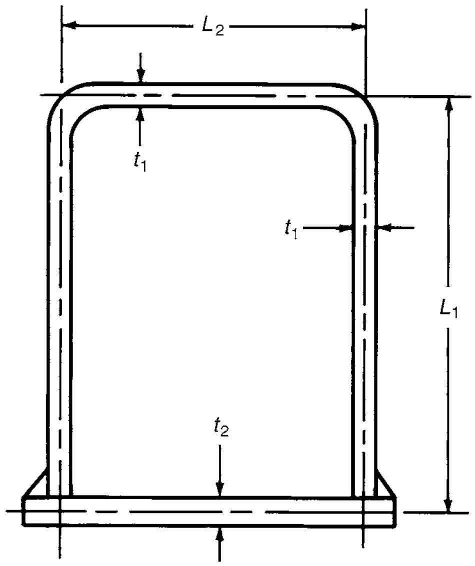
Torsional resistance increases markedly with closed cross sections, such as circular or rectangular tubing. Consequently, the angular twist is greatly reduced because it varies inversely with torsional resistance. The torsional resistance, R, of any closed box shape enclosing only one cell can be estimated by the following procedure using the equation presented in Figure 5.12. A dotted line is drawn through the mid-thickness around the section, as shown. The area, A, is enclosed by the dot-dash lines. The cross section of the member is divided into convenient lengths, L_n, having thicknesses t_n. The ratios of these individual lengths to their corresponding thicknesses are then determined.

Table 5.5
Calculated and Actual Angle of Twist

	Angle of Twist, Degrees	
	Strip*	I-Section†
Calculated using torsional resistance (R)	21.8	7.3
Actual twist	22	9.5

*0.055 in. by 2 in. (1.4 mm by 50.8 mm).
† Made of three of the strips.

Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Table 2-3.



$$R = \frac{4A^2}{\Sigma\,(L_n/t_n)} = \frac{4L_1^2L_2^2}{2\,(L_1/t_1) + (L_2/t_1) + (L_2/t_2)}$$

Key:
R = Torsional resistance, in.^{4} (mm^4)
A = Enclosed area, in.^{2} (mm^2)
L_n = Distance of each side, in. (mm)
t_n = Thickness of corresponding side, in. (mm)
L_1 = Distance of Side 1, in. (mm)
L_2 = Distance of Side 2, in. (mm)
t_1 = Thickness of Side 1, in. (mm)
t_2 = Thickness of Side 2, in. (mm)

Figure 5.12—Torsional Resistance, *R*, of a Closed Box Section

The torsional resistance can then be obtained using the following equation:

$$R = \frac{4A^2}{\sum\left(\frac{L_n}{t_n}\right)} \tag{5.9}$$

where

R = Torsional resistance, in.^{4} (mm^4);
A = Enclosed area, in.^{2} (mm^2);
L_n = Distance of each side, in. (mm); and
t_n = Thickness of corresponding side, in. (mm).

The maximum shear stress in a rectangular section under torsion occurs on the surface at the center of the long side. When the unit angular twist is known, the following expression is used to find the maximum shear stress at the surface of a rectangular part:

$$\tau = \theta' t G = \frac{Tt}{R} \tag{5.10}$$

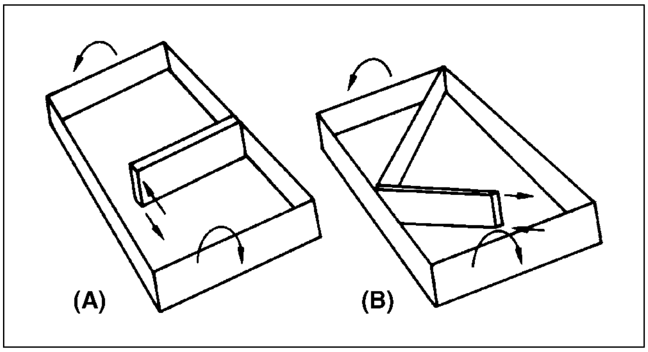
where

τ = Maximum shear stress, ksi (MPa);
θ' = Unit angular twist, radians/in. (radians/mm);
G = Modulus of elasticity in shear, ksi (MPa);
T = Applied torque, kips in. (kN mm);
t = Thickness of the section, in. (mm); and
R = Torsional resistance, in.^{4} (mm^4).

This equation can be applied to a flat plate or a rectangular area of an open structural shape (channel, angle, I-beam). In the latter case, R denotes the torsional resistance of the whole structural shape.

Diagonal Bracing. Diagonal bracing is very effective in preventing the twisting of frames. A simple explanation of the effectiveness of diagonal bracing involves an understanding of the directions of the forces involved.

A flat bar of steel has little resistance to twisting, but has exceptional resistance of bending (stiffness) about its major axis. Transverse bars or open sections at 90° to the main members are not effective for increasing the torsional resistance of a frame because, as shown in Figure 5.13(A), they contribute only relatively low torsional resistance. However, if the bars are oriented diagonally at 45° across the frame, as in Figure 5.13(B), the twisting of the frame is resisted by the stiffness of the bars. To be effective, the diagonal braces must have good bending stiffness perpendicular to the plane of the frame.

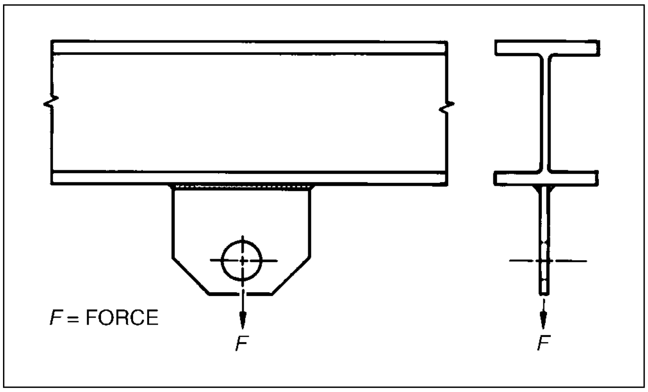


Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-24.

Figure 5.13—Frames Subjected to Torsion with (A) Transverse Rib Bracing and (B) Diagonal Bracing

TRANSFER OF FORCES

Loads create forces that must be transmitted through the structure to suitable places for counteraction. Designers must therefore know how to provide efficient pathways. One of the basic rules of welding design is that a force applied transversely to a member ultimately enters the portion of the section that lies parallel to the applied force. An example is a lug welded parallel to the length of a beam, as depicted in Figure 5.14. The portion of the beam that is parallel to the applied force, F, is the web. The force in the lug is easily transferred through the connecting welds into the web. No additional stiffeners or attaching plates are required.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-27.

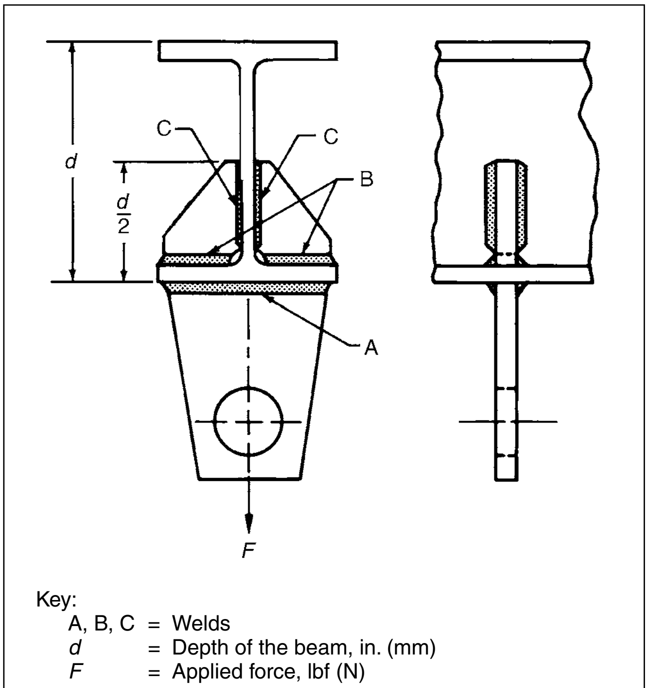
Figure 5.14—Lug Welded Parallel to the Length of a Beam; No Additional Stiffeners Are Required

Suppose, however, that the lug were welded to the beam flange at right angles to the length of the beam, as shown in Figure 5.15(A). The outer edges of the flange tend to deflect rather than support much load. This forces a small portion of the weld in line with the web to carry a disproportionate share of the load, as can be observed in Figure 5.15(B).

To distribute the load on the attachment weld uniformly, two stiffeners can be aligned with the lug and then welded to the web and to the adjacent flange of the beam. This procedure is illustrated in Figure 5.16. The stiffeners reinforce the bottom flange and transmit part of the load to the web of the beam. The welds labeled "B" and "C" in Figure 5.16 must be designed to carry the portion of applied force, *F*, that is not directly transferred to the web by Weld "A."

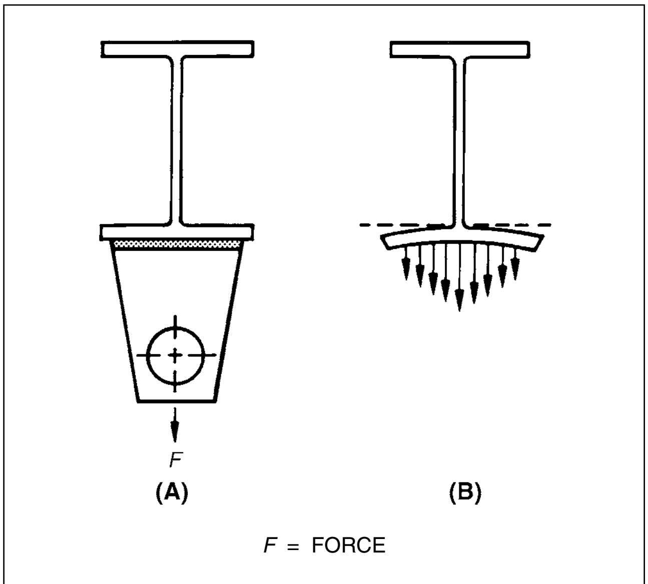
If a force is to be applied to a beam parallel to the flanges by a plate welded to the web, as indicated in Figure 5.17, unacceptable distortion may result. The required weld (or web) strength must be estimated by means of a yield-line analysis of the web.

On the other hand, orienting the attachment plate transverse to the web and welding it to the web only result in a low-strength connection because of the high concentrations of stress at the ends of the weld. This is depicted in Figure 5.18.



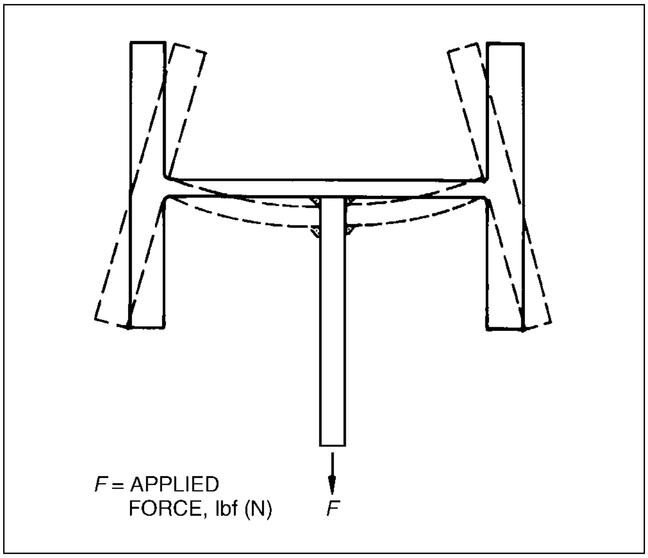
Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-29.

Figure 5.16—Additional Stiffeners Required to Transmit a Load to the Web of the Beam



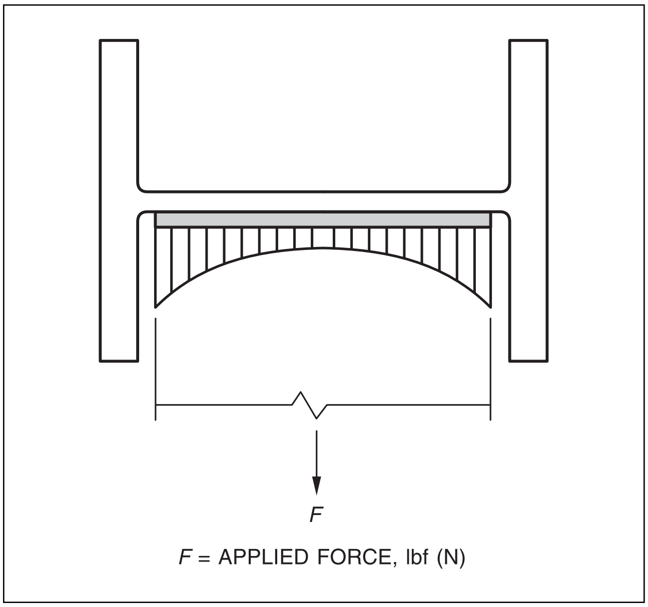
Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-28.

Figure 5.15—Transfer of Force from a Welded Lug to a Beam: (A) Lug Welded to a Flange Transverse to the Beam Length; (B) Resulting Loading and Deflection of the Flange



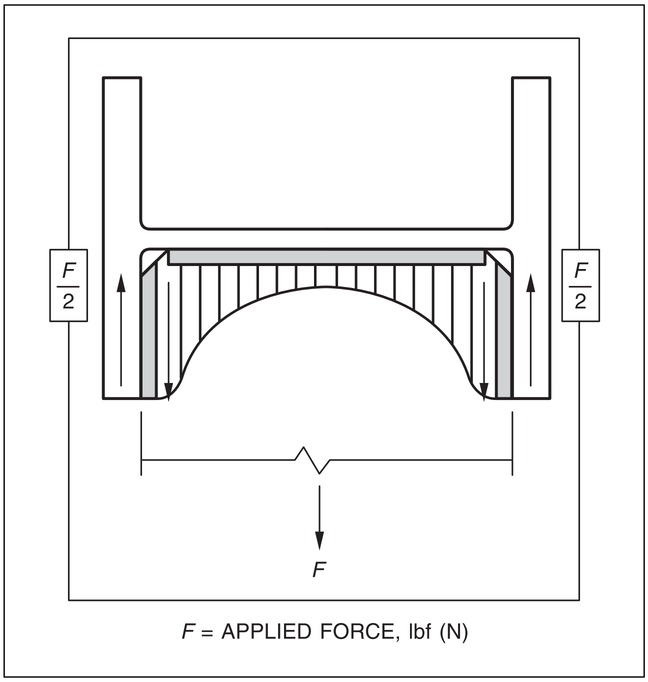
Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-30.

Figure 5.17—Distortion of a Beam Caused by a Loaded Attachment to the Web



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-31.

Figure 5.18—Stress Distribution with an Attachment Welded to the Web



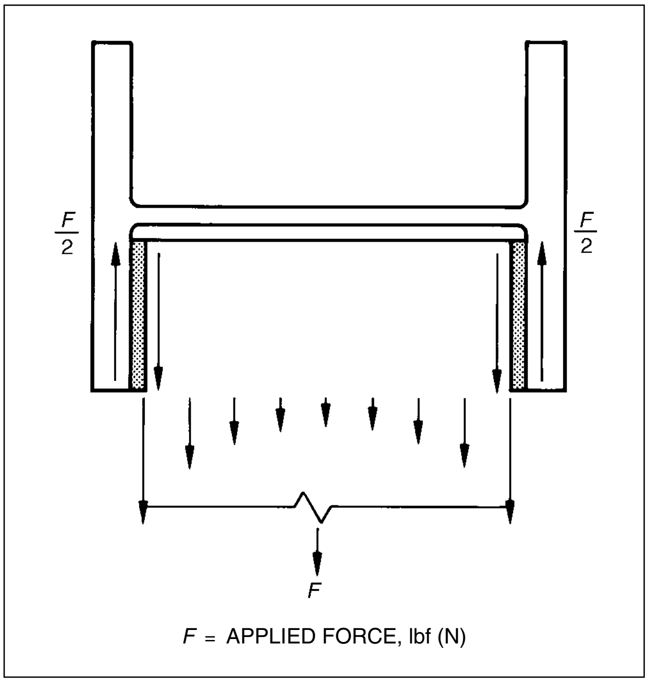
Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-32.

Figure 5.19—Stress Distribution with an Attachment Welded to the Web and Flanges

Similarly, if the attachment is welded to both flanges and the web without a stiffener on the opposite side of the web, the weld must not be sized on the assumption of uniform stress along the total length of weld. Only negligible loads are transferred across most of the width of the web, as shown in Figure 5.19. Most of the load is transmitted to the two flanges through the attachment welds by shear.

If an attachment is made by welding to the flanges only, the problem is not the distribution of stress in the weld but rather the effects of shear lag in the attachment. This would cause high stress concentrations in the plate near the flange edges, as illustrated in Figure 5.20. The plate should be designed on the basis of reduced allowable stresses or reduced effective area. An exception would be if the length of each weld along the edges of the plate were more than the width of the plate, as required by the AISC specifications.[31]

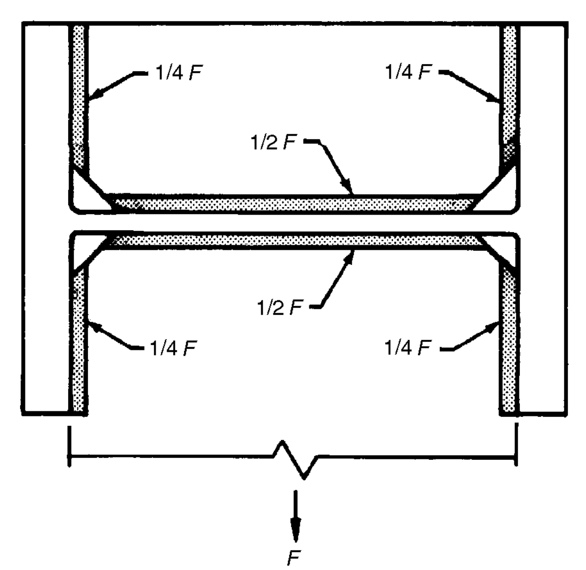
For large forces, it might be necessary to place a stiffener on the opposite side of the web, as illustrated in Figure 5.21. In this case, both the plate and the stiffener must be welded to the web as well as to the



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-31.

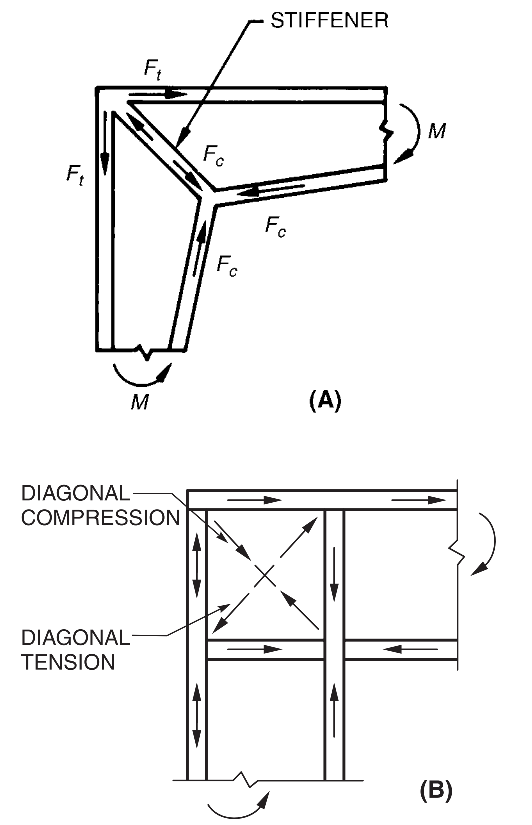
Figure 5.20—Stress Distribution with Attachment Welded to Flanges Only

31. American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-32.

Figure 5.21—Stiffener on the Opposite Side of the Attachment; Welded as Shown for Large Loads



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-34.

Figure 5.22—Designs for the Knee of a Rigid Frame with (A) Diagonal Stiffeners and (B) Vertical and Horizontal Stiffeners

flanges. With this detail, the length of welds parallel to the direction of applied stress is effectively doubled, and the shear lag effect in the attachment is greatly reduced.

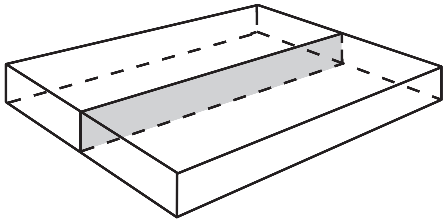
In all cases, the fillet welds joining the plate to the beam flanges must not extend around the plate along the edges of the flanges. Abrupt changes in weld direction on two planes can intensify stress concentrations.

When a force in a structure changes direction, a force component is involved. This is illustrated in Figure 5.22, which depicts the knee of a rigid frame subjected to a bending moment. The compressive force in the interior flanges must change direction at the knee. To transfer this component, diagonal stiffeners are placed on both sides of the web at the intersections of the two flanges, as shown in Figure 5.22(A). An alternate detail using vertical and horizontal stiffeners to accomplish the same effect is shown in Figure 5.22(B). The compressive force component in the web and stiffeners balances the change in the direction of the tensile force in the outer flanges.

DESIGN OF WELDED JOINTS

The loads in a welded structure are transferred from one member to another through the welds placed in the joints. The various types of joints used in welded construction and the applicable welds are shown in Figure 5.23.

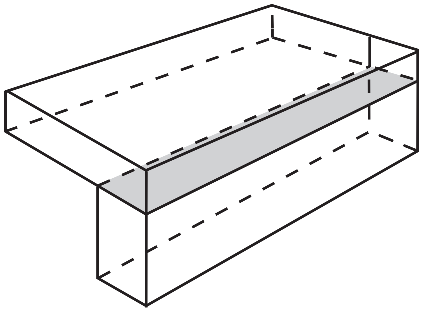
The configurations of the various welds are illustrated in Figures 5.24, 5.25, and 5.26. Combinations of welds may be used to connect a joint, depending upon the strength requirements and loading conditions. For example, fillet and groove welds are frequently combined in corner and T-joints.



APPLICABLE WELDS

BEVEL-GROOVE	SQUARE GROOVE
FLARE-BEVEL-GROOVE	U-GROOVE
FLARE-V-GROOVE	V-GROOVE
J-GROOVE	BRAZE

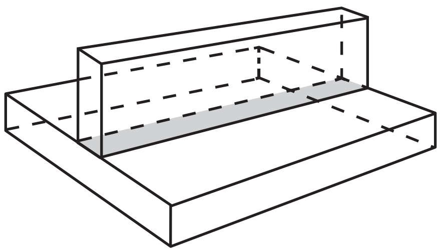
(A) Butt Joint



APPLICABLE WELDS

FILLET	V-GROOVE
BEVEL-GROOVE	PLUG
FLARE-BEVEL-GROOVE	SLOT
FLARE-V-GROOVE	SPOT
J-GROOVE	SEAM
SQUARE-GROOVE	PROJECTION
U-GROOVE	BRAZE

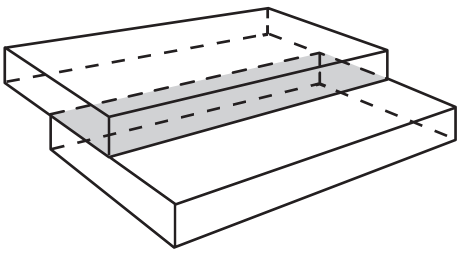
(B) Corner Joint



APPLICABLE WELDS

FILLET	SLOT
BEVEL-GROOVE	SPOT
FLARE-BEVEL-GROOVE	SEAM
J-GROOVE	PROJECTION
SQUARE-GROOVE	BRAZE
PLUG	

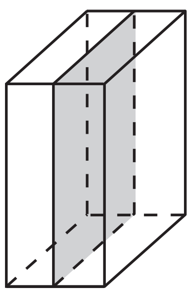
(C) T-Joint



APPLICABLE WELDS

FILLET	SLOT
BEVEL-GROOVE	SPOT
FLARE-BEVEL-GROOVE	SEAM
J-GROOVE	PROJECTION
PLUG	BRAZE

(D) Lap Joint



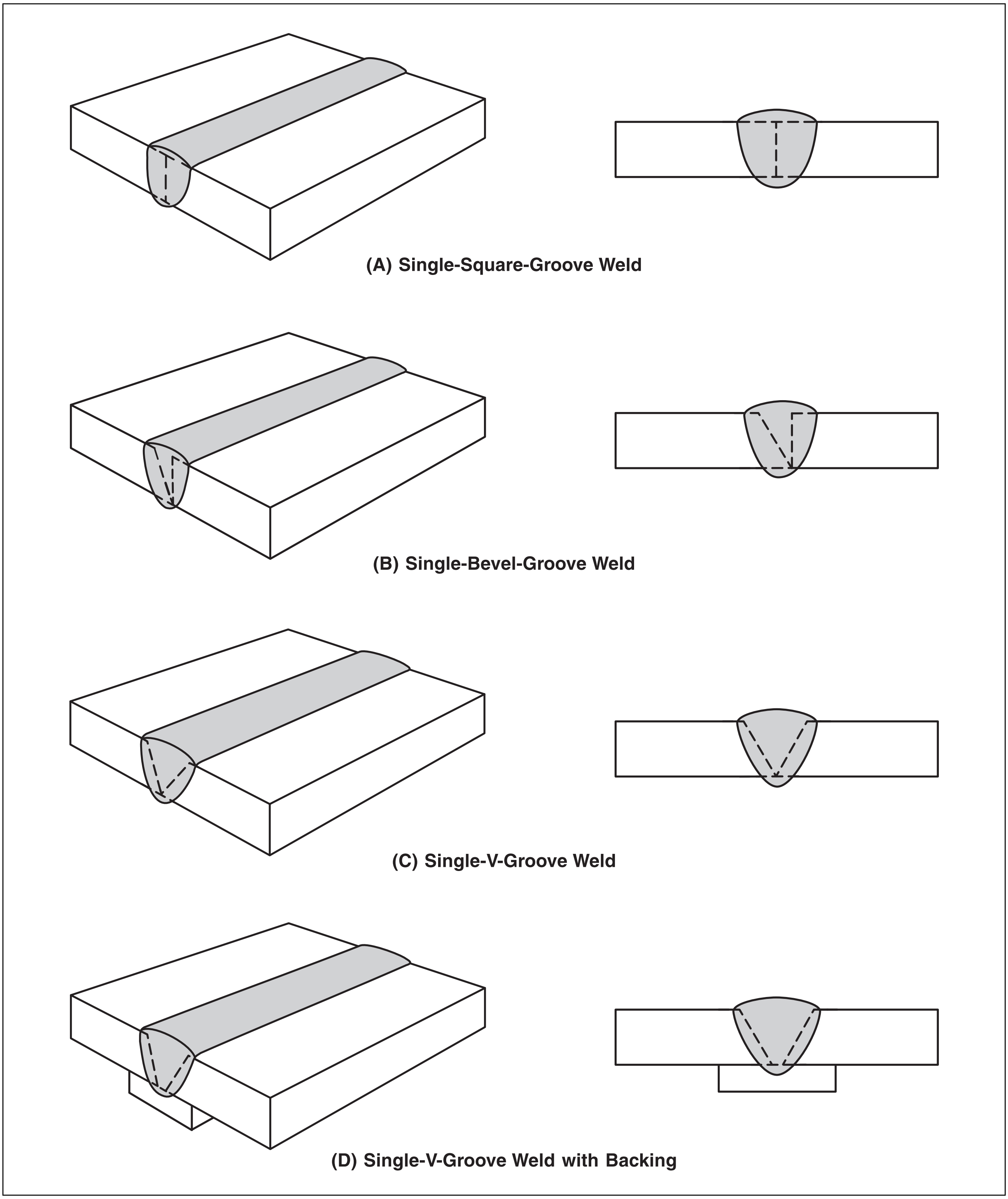
APPLICABLE WELDS

BEVEL-GROOVE	V-GROOVE
FLARE-BEVEL-GROOVE	EDGE
FLARE-V-GROOVE	SEAM
J-GROOVE	SPOT
SQUARE-GROOVE	PROJECTION
U-GROOVE	SEAM

(E) Edge Joint

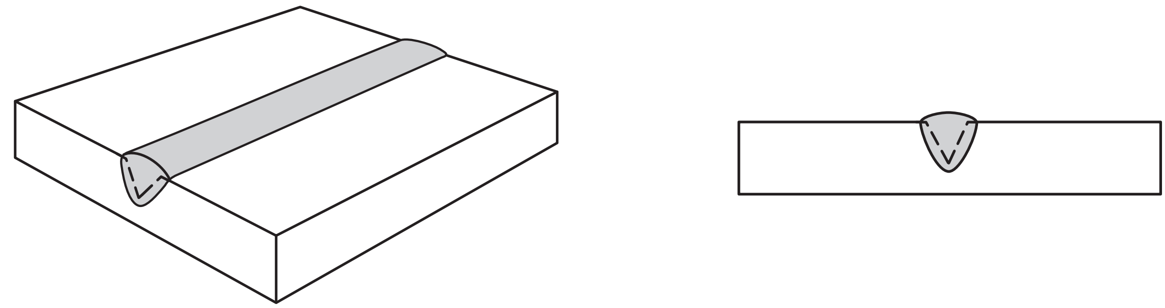
Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 1.

Figure 5.23—Types of Joints

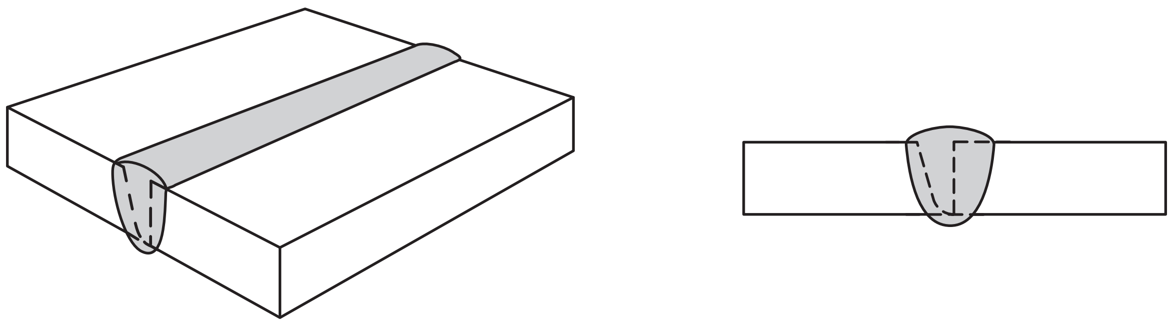


Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 8.

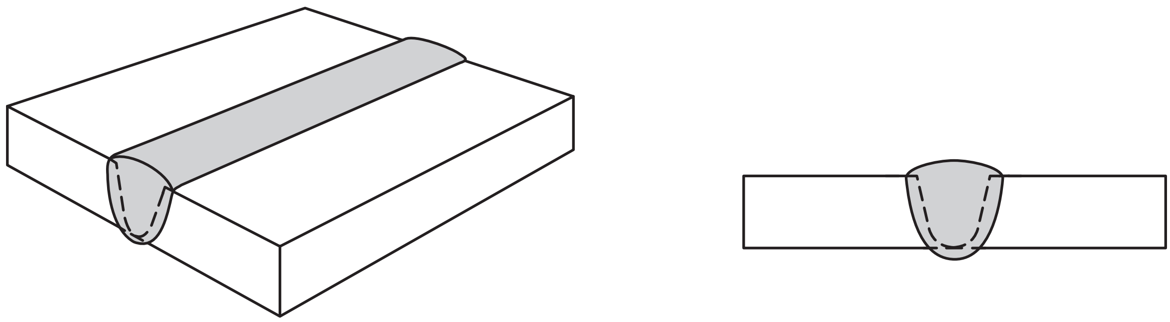
Figure 5.24—Single-Groove Welds



(E) Single-V-Groove Weld on a Surface



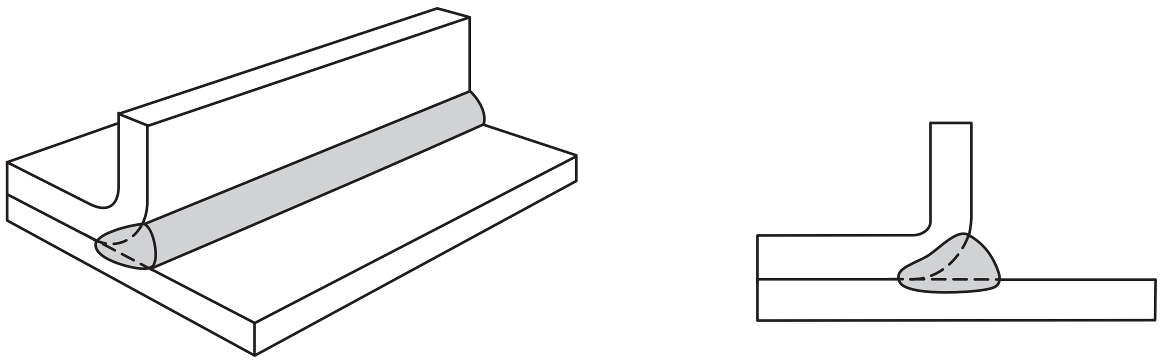
(F) Single-J-Groove Weld



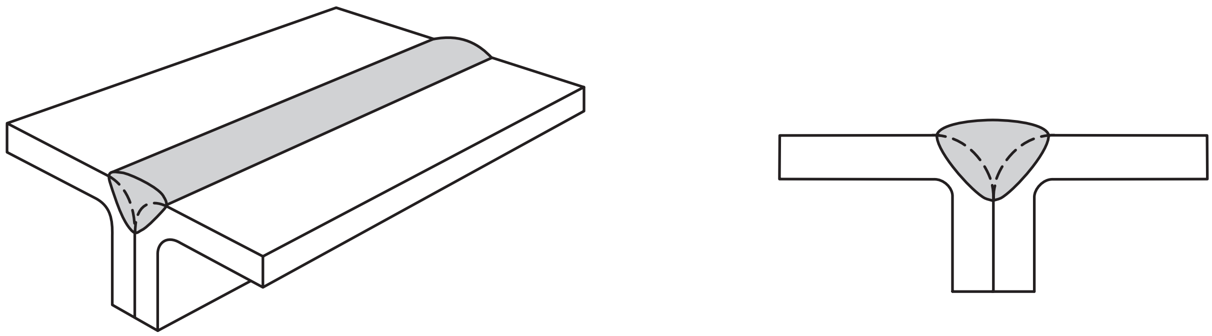
(G) Single-U-Groove Weld

Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 8.

Figure 5.24 (Continued)—Single-Groove Welds



(H) Single-Flare-Bevel-Groove Weld



(I) Single-Flare-V-Groove Weld

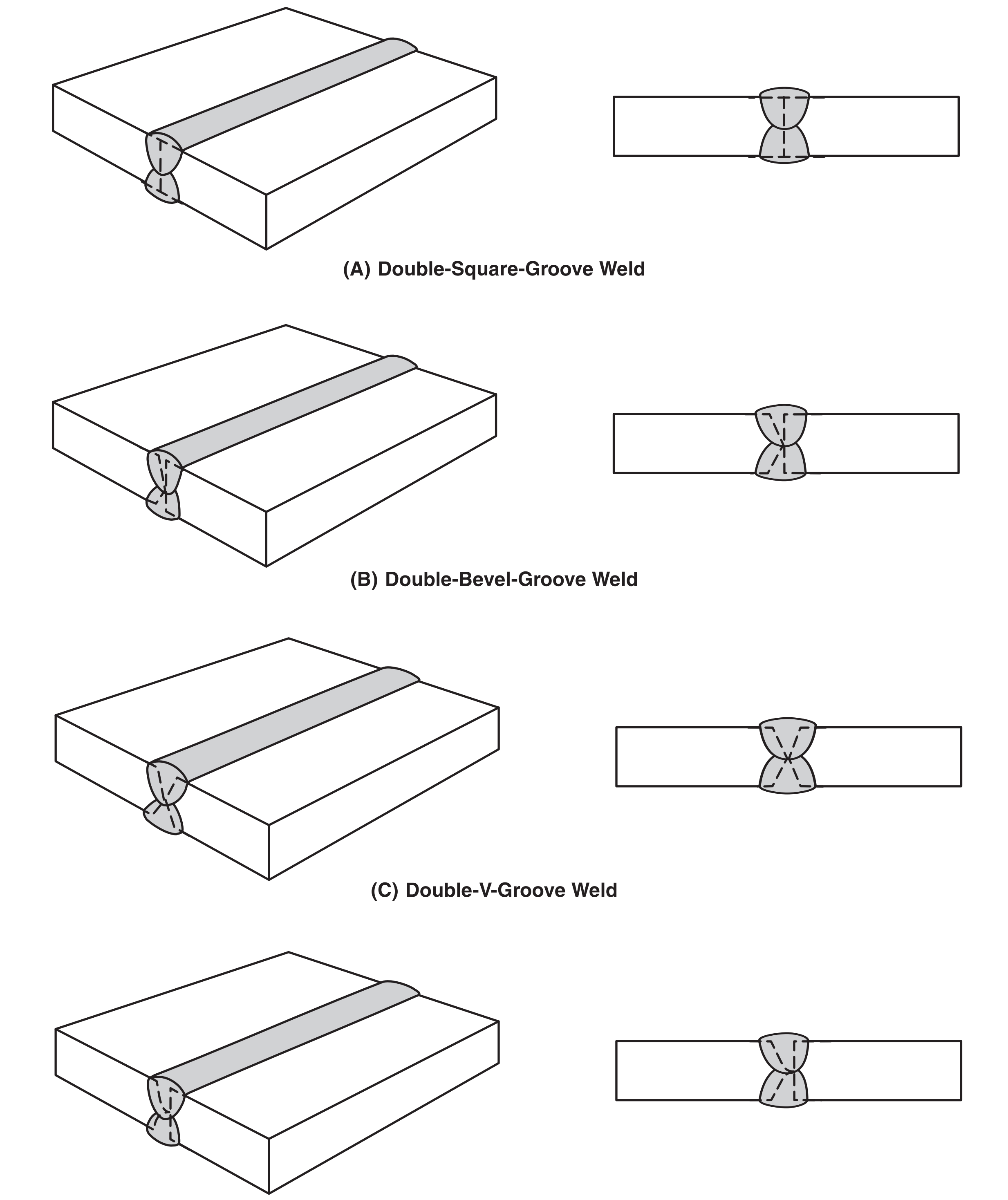
Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 8.

Figure 5.24 (Continued)—Single-Groove Welds

Welded joints are designed primarily to meet the strength and performance requirements for the service conditions under which they must perform. The manner in which the stress will be applied in service—whether in tension, compression, shear, bending, torsion, or a combination of these—must be considered. When designing for fatigue, different joint details may be required. Joints should be designed to avoid stress raisers and minimize residual stresses. Conditions of corrosion or erosion require joints that are free of irregularities, crevices, and other areas that make them susceptible to such forms of attack.

Certain welding processes, in conjunction with certain related types of joints, have repeatedly provided satisfactory performance. Therefore, these processes and joints are given prequalified status, provided the weld procedures meet other specific requirements of *Structural Welding Code—Steel*, AWS D1.1.[32] However, the use of a prequalified welding process or procedure and joint geometry on a particular design or

32. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel*, AWS D1.1, Miami: American Welding Society.



(A) Double-Square-Groove Weld

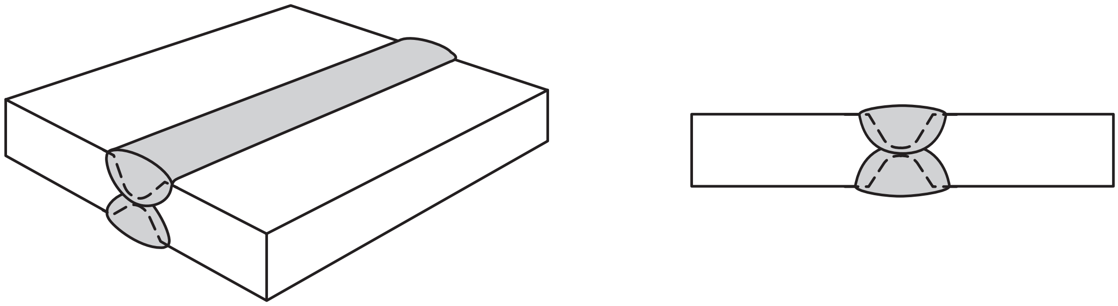
(B) Double-Bevel-Groove Weld

(C) Double-V-Groove Weld

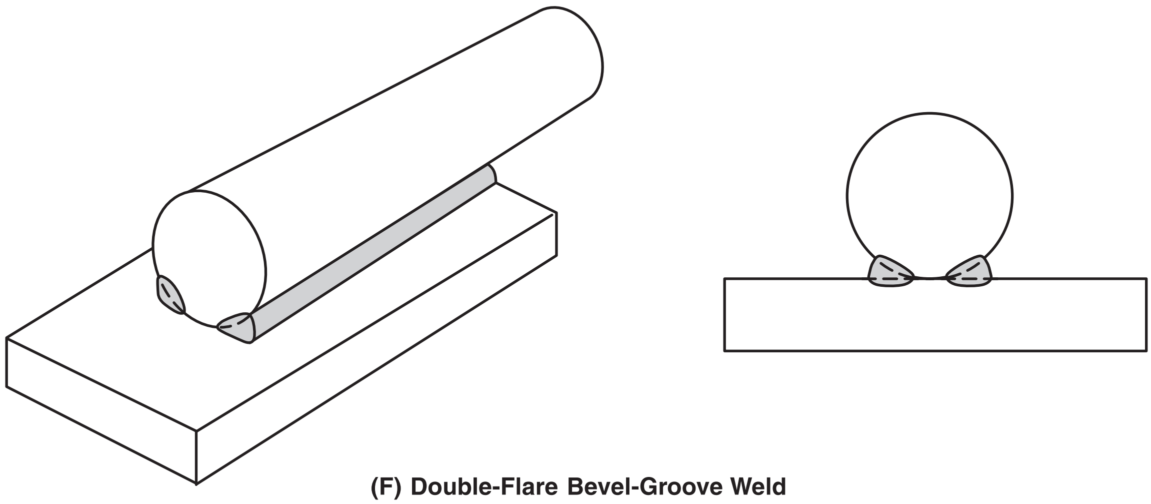
(D) Double-J-Groove Weld with Backing

Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 9.

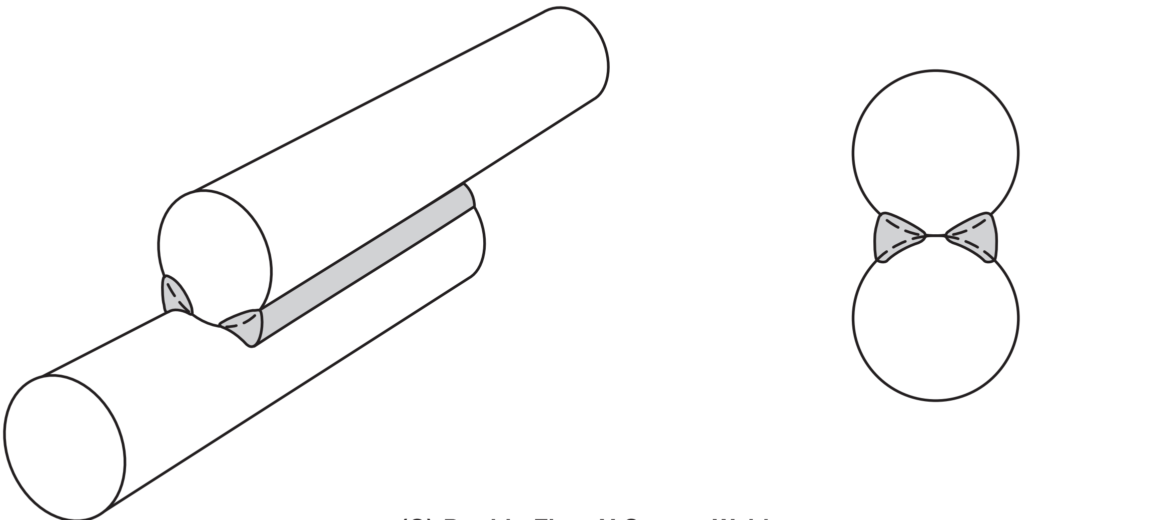
Figure 5.25—Double-Groove Welds



(E) Double-U-Groove Weld



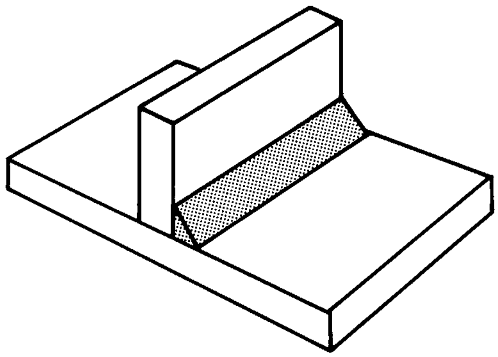
(F) Double-Flare Bevel-Groove Weld



(G) Double-Flare-V-Groove Weld

Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 9.

Figure 5.25 (Continued)—Double-Groove Welds



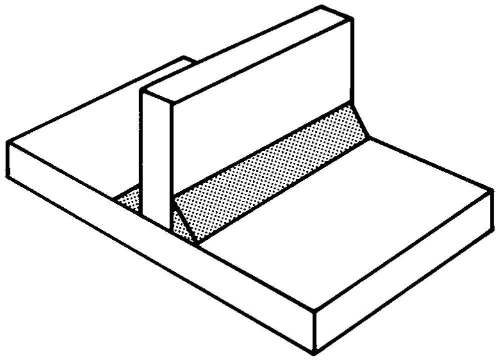


Figure 5.26—Fillet Welds: (A) Single Fillet and (B) Double Fillet

application does not guarantee satisfactory results. The designer must also consider the following questions:

1. Is the joint accessible to welders and inspectors;
2. Does the design consider the economic factors of welding;
3. Will shrinkage stresses lead to excessive joint or member distortion; and
4. Will shrinkage stresses cause lamellar tearing, cracking of the heat-affected zone, or other material problems?

GROOVE WELDS

The selection of groove weld type and configuration is influenced by accessibility, economy, the particular design of the structure being fabricated, distortion control, and the type of welding process to be used.

Square-groove welds, shown in Figures 5.24(A) and 5.25(A), are economical, provided satisfactory soundness and strength can be obtained. However, their use is limited to relatively thin material. For thick joints, the edge of one or more members must be prepared to a particular geometry to provide accessibility for welding and ensure the desired soundness and strength.

In the interest of economy, joint designs should be selected with root openings and groove angles that require the smallest amount of weld metal while providing sufficient accessibility to achieve sound welds. The selection of a root opening and groove angle is also greatly influenced by the metals to be joined, the location of the joint in the weldment, distortion and shrinkage control, and the performance required.

Welds in J- and U-groove joints may be used to minimize the amount of weld metal required when the savings are sufficient to justify the more costly preparation of the edges, particularly in the welding of thick sections. The narrower groove angle used in J- and U-groove welds, which is possible because of the wider, rounded root, also reduces angular distortion. Bevel- and J-groove welds are more difficult to weld than V- and U-groove welds because one edge of the groove is perpendicular to the surface of the workpiece, requiring the electrode to be angled obliquely into the groove toward the vertical face. For some processes, single-bevel groove welds are prequalified only in the flat position.

The amount of joint penetration, or weld size, and the strength of the filler metal determine the strength of the welded joint. Welded joints must be designed to provide sufficient strength to transfer the design forces as well as ensure proper performance under cyclic or other severe loads, when applicable. This frequently requires that the welded joint provide strength equal to that of the base metal. To accomplish this, designs that require complete penetration through the members being joined are commonly used.

The selection of the details of welding grooves—the groove angle, root face, root opening, and so forth—depends upon the welding process and procedure to be used and the physical properties of the base metals being joined. Some welding processes characteristically provide deeper joint penetration than others. Some metals, such as copper and aluminum, have relatively high thermal conductivities. These metals require greater heat input for welding than other metals with lower thermal properties.

The various types of groove welds have certain advantages and limitations with respect to their applications. In the following discussion, comments on design, joint penetration, and effective throat apply to the joining of carbon steel by shielded metal arc (SMAW), gas metal arc (GMAW), flux cored arc (FCAW), and submerged arc welding (SAW). Joint penetration with base metals other than carbon steel may vary due to the properties of the base metals.

Complete Joint Penetration Groove Welds

Groove welds with complete joint penetration are suitable for all types of loading, provided they meet the acceptance criteria for the application. In most cases, to ensure complete joint penetration with double-groove and single-groove welds without a backing bar, the root of the first weld must be backgouged to sound metal before making a weld pass on the other side.

When properly made using filler metals that match the strength of the base metal, complete penetration groove welds develop the strength of the base metal. The allowable stress range for complete joint penetration groove welds in cyclic applications depends upon the joint detail, the direction of stress, the finishing of the weld, and the testing performed.

Partial Joint Penetration Groove Welds

Partial joint penetration groove welds have an unwelded portion at the root of the weld. This unwelded portion constitutes a stress raiser, having significance when cyclic loads are applied transversely to the joint. This is reflected in the low allowable fatigue stress range that characterizes these welds. However, when the load is applied parallel to the weld axis, a higher stress range is permitted.

With single-sided partial penetration groove welds, the eccentricity of shrinkage forces in relation to the center of gravity of the section can result in angular distortion upon cooling after welding. This same eccentricity also tends to cause the rotation of a transverse axial load across the joint. This type of rotation must be minimized both during fabrication and in service.

For static loading, the allowable stresses in partial joint penetration groove welds depend upon the type and direction of loading and the applicable code requirements. Under *Structural Welding Code—Steel*, AWS D1.1:2000, the allowable tensile stress in the weld when loaded in tension transverse or normal to the axis of the weld is 0.30 times the nominal tensile strength of the filler metal. However, the allowable tensile stress in the base metal may not exceed 0.60 times the yield strength of the base metal.[33]

The allowable shear stress of the weld metal may not exceed 0.30 times the nominal tensile strength of the filler metal. However, the allowable shear stress on the throat of the weld metal may not exceed 0.40 times the yield strength of the base metal.

Joints welded from one side should not be used in bending with the root in tension, nor should they be subjected to transverse fatigue or impact loading. When loaded transverse to the weld axis, partial joint penetration groove welds are recommended only for static loads. When loaded parallel to the weld axis, they may be used in both static and cyclic applications. Single-sided partial penetration joints should not be exposed to corrosive conditions at the root.

For design purposes, the effective throat is never greater than that of the depth of joint preparation. It may be less when the groove angle is small and the process and weld position used have insufficient penetration to consistently extend to the root of the joint.

V-GROOVE WELDS

The strength of a V-groove weld, as with all groove welds, depends upon the extent of joint penetration. For all types of loading, full-strength joints can be obtained with complete joint penetration. V-groove welds are generally considered economical when the depth of preparation of the groove does not exceed approximately 3/4 in. (19 mm). When the depth of joint preparation exceeds this amount, J- or U-groove weld details may be more economical.

BEVEL-GROOVE WELDS

Single-bevel-groove welds have characteristics similar to V-groove welds with respect to properties and applications. The bevel type requires less joint preparation and weld metal; therefore, it is generally more economical. However, the disadvantage of this type of weld is that the technique required to obtain complete fusion with the perpendicular face of the joint is more challenging. In addition, satisfactory backgouging of the root of the first weld pass may be harder to accomplish. In the horizontal position, the unbeveled face should be placed on the lower side of the joint to obtain good fusion.

The design for a double-bevel joint is economical when the depth of the groove does not exceed about 3/4 in. (19 mm) and the joint thickness is 1-1/2 in. (38 mm) or less. For thicker sections or deeper grooves, a double-J joint design may be more economical.

U- AND J-GROOVE WELDS

U-groove welds and J-groove welds are used for similar applications. However, with U-grooves, complete fusion is easier to obtain. J-groove welds have the same characteristics as similar bevel-groove welds. However, they may be more economical for thicker sections, pro-

33. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel*, 2000, AWS D1.1:2000, Miami: American Welding Society.

vided the savings in deposited weld metal exceeds the cost of machining or gouging the edge preparation. Their use may be best suited to the horizontal position in some applications, with the unprepared edge on the lower surface.

FILLET WELDS

Design permitting, fillet welds may be used in preference to groove welds for economy. Fillet-welded joints are very simple to prepare from the standpoint of edge preparation and fitup, although groove-welded joints sometimes require less welding. If the load requires a fillet weld of approximately 5/8 in. (16 mm) or larger, a groove weld should be considered alone or in combination with a fillet weld to provide the required effective throat. In this case, the reduction in welding costs may be sufficient to offset the cost of joint preparation. When the smallest practicable continuous fillet weld results in a joint strength greater than that required, intermittent fillet welding may be used to avoid overwelding unless continuous welding is required by the service conditions.

As shown in Figure 5.27, the size of a fillet weld is measured by the length of the legs of the largest right triangle that may be inscribed within the cross section of the weld. The effective throat, which is a better indication of weld shear strength, is the shortest distance between the root of the weld and the weld face. The effective area of a fillet weld is based upon the effective throat and the length of the weld. The strength is determined by the effective area and the nominal tensile strength of the filler metal. The actual throat may be larger than the theoretical throat by virtue of joint penetration beyond the root of the weld. Submerged arc and flux cored arc welding are particularly deep penetrating processes. Under certain conditions, several standards[34] allow consideration of the extra penetration that these processes provide as part of the effective throat in fillet welds.

Applications

As fillet welds are economical, they are used to join corner, T-, and lap joints. Edge preparation is not required, though surface cleaning may be needed. Fillet welds are generally applicable for the transfer of shear forces parallel to the axis of the weld as well as the transfer of static forces transverse to the axis of the weld. Fillet welds may be used in skewed T- or corner joints having a dihedral angle between 60° and 135°. Below 60°, these welds may be used but are considered partial-joint penetration groove welds. In this case, a Z-loss factor should be used.[35]

Fillet welds are always designed on the basis of shear stress on the throat, regardless of the direction of applied force relative to the axis of the weld. The maximum shear stress is calculated based on the effective area of the weld. In the case of steel, the maximum shear stress is normally limited to 30% of the nominal (classification) tensile strength of the filler metal.

Weld Size

Fillet welds must be large enough to carry the applied load and avoid cracking by accommodating the shrinkage of the weld metal during cooling, particularly with highly restrained thick sections. To minimize distortion and welding costs, however, the specified size of the fillet weld should not be excessive. Welds in lap joints must not exceed the thickness of the exposed edge, which should be visible after welding.

Fillet welds may be designed with unequal leg sizes to provide the required effective throat or the needed heat balance for complete fusion with unequal base metal thicknesses.

Single and Double Fillet Welds

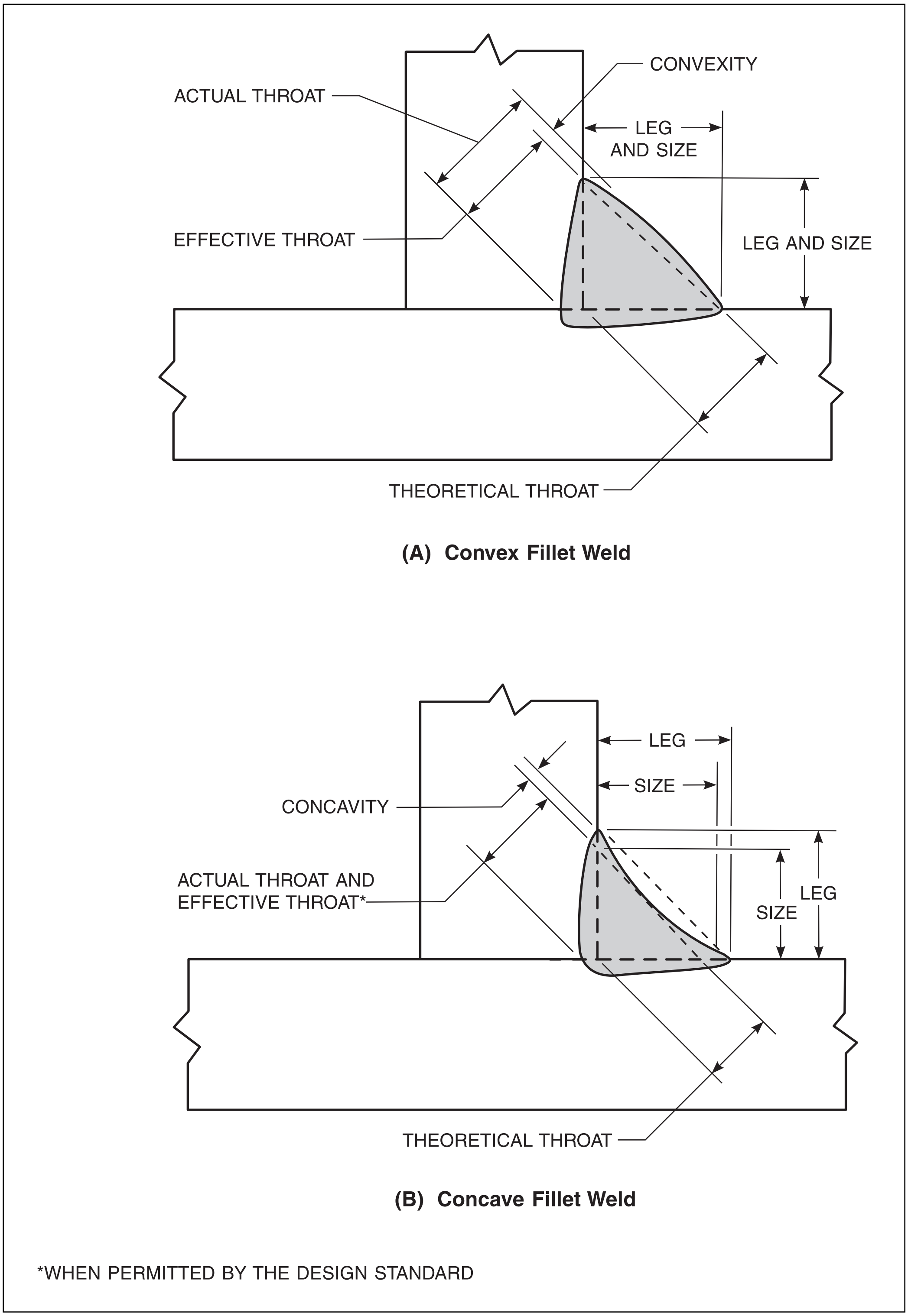
Fillet welds used on one side of the joint only are limited in application. Figure 5.28 presents examples of prohibited applications of the one-sided fillet weld. As shown in this figure, bending moments that result in tension stresses in the root of a fillet weld should be avoided because of the notch condition. For this reason, one-sided fillet welds should not be used with lap joints that can rotate about the longitudinal axis under load, nor should they be subjected to impact loads.

When access permits, smaller fillet welds on each side of the joint are preferable to one large single fillet weld. Full-plate strength can often be obtained economically with single fillet welds under static loading. The double fillet welding of corner and T-joints limits the rotation of the members about the longitudinal axis of the joint and minimizes tension stresses at the root of the welds. These types of joints can be cyclically loaded parallel to the weld axes.

Lap joints should have a minimum overlap of about five times the thickness of the base metal to limit joint rotation under load.

34. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Aluminum,* ANSI/AWS D1.2, Miami: American Welding Society; American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Earthmoving and Construction Equipment,* ANSI/AWS D14.3, Miami: American Welding Society; and American Institute of Steel Construction (AISC), *Manual of Steel Construction: Load and Resistance Factor Design,* Vols. 1 and 2, Chicago: American Institute of Steel Construction.

35. For further information, see American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001. *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 25.

Figure 5.27—Fillet Weld Sizes: (A) Convex Fillet and (B) Concave Fillet

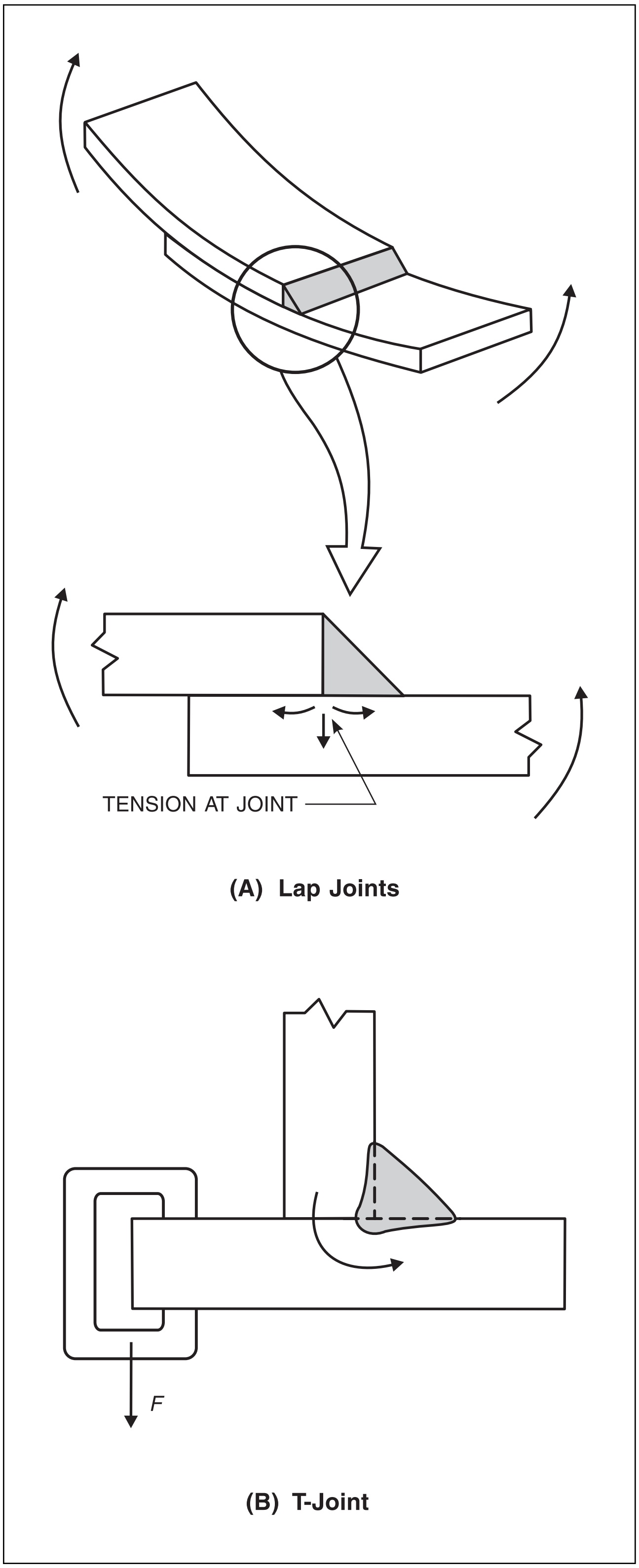


Figure 5.28—Prohibited Applications of the One-Sided Fillet Weld

SELECTION OF WELD TYPE

Weldment designers must frequently decide whether to use fillet or groove welds in a design. Cost and performance are the major considerations. Fillet welds, like those shown in Figure 5.29(A), are easy to apply and require no special edge preparation. They can be made using large-diameter electrodes with high welding currents for high deposition rates. In comparison, double-bevel-groove welds, like those shown in Figure 5.29(B), have less cross-sectional area than that of fillet welds. However, double-bevel-groove welds require edge preparation and the use of small-diameter electrodes to make the root pass.

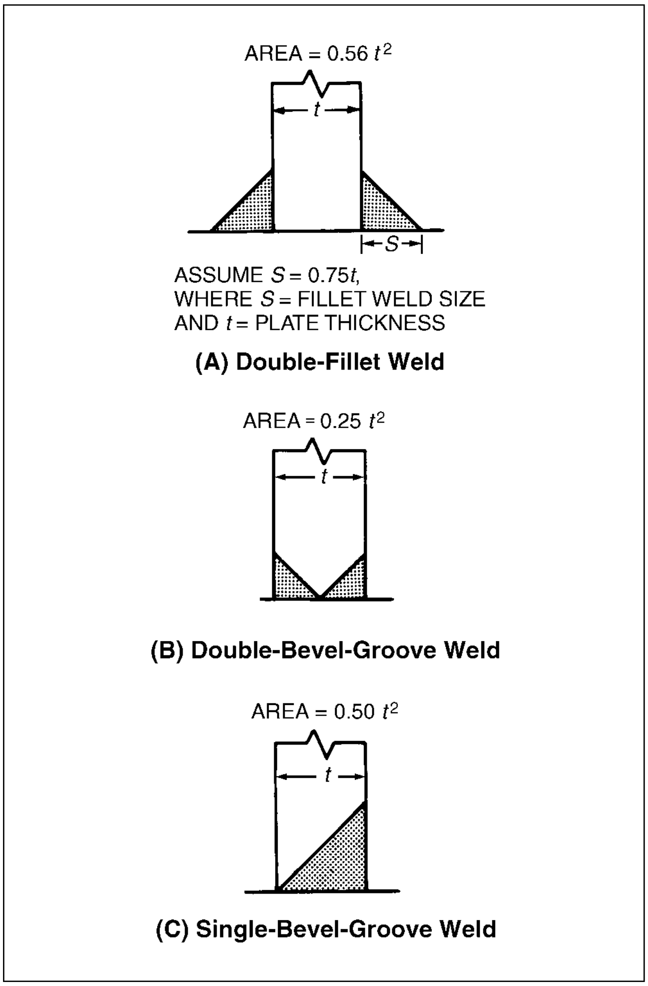


Figure 5.29—Comparison of Weld Quantities for Three Conditions of T-Joints

Single-bevel-groove welds, such as that depicted in Figure 5.29(C), require approximately the same amount of weld metal as single fillet welds like those shown in Figure 5.29(A). Thus, the single-bevel-groove offers no apparent economic advantage. Disadvantages include the required edge preparation and a low-deposition root pass. In addition, groove welds usually require nondestructive examination (NDE), which increases the total cost compared to the costs associated with visual inspection of the welds. From a performance standpoint, however, groove welds provide for the direct transfer of force through the joint.

For thick plates, the cost of a double fillet welded joint may exceed that of a single-bevel-groove weld. In addition, if the joint can be positioned so that the groove weld can be made in the flat position, a single fillet weld would require more weld metal than a single-bevel-groove weld.

The use of estimating curves, which is based upon the actual cost of joint preparation, positioning, and welding, is a technique that is used to determine the plate thickness for which the various types of joint details are most economical. A sample set of curves is illustrated in Figure 5.30. The intersection of the fillet weld curve with the groove weld curves is a point of interest. The validity of the information is dependent on the accuracy of the cost data at a particular fabricating plant.

The combined double-bevel-groove and fillet weld joint, illustrated in Figure 5.31, is theoretically a full-strength weld prepared for a submerged arc weld. The plate edge is beveled to 60° on both sides to a depth of 30% of the thickness of the plate. After the groove on each side is welded, it is reinforced with a fillet weld of equal area and shape. The total effective throat of the weld is equal to the plate thickness. This partial joint penetration groove weld has only about 60% of the weld metal of a full-strength single fillet weld. It requires joint preparation, but the wide root face and groove angle permit the use of large electrodes and high welding currents.

Full-strength welds are not always required in a weldment, and increased economic benefit can often be achieved by using smaller welds where applicable and permissible. Figure 5.32 presents examples of the manner in which cost savings can be obtained by modifying the joint details. With equal effective throats (shear area), fillet welds such as that shown in Figure 5.32(A) require twice the weld metal needed for the 45° partial joint penetration single-bevel-groove weld, such as that depicted in Figure 5.32(B). The latter weld may not be as economical as the fillet weld, however, because of the cost of edge preparation. In addition, some welding standards limit the effective throat of this type of weld to less than the depth of the bevel with certain welding processes and positions because of the possibility of incomplete root penetration.

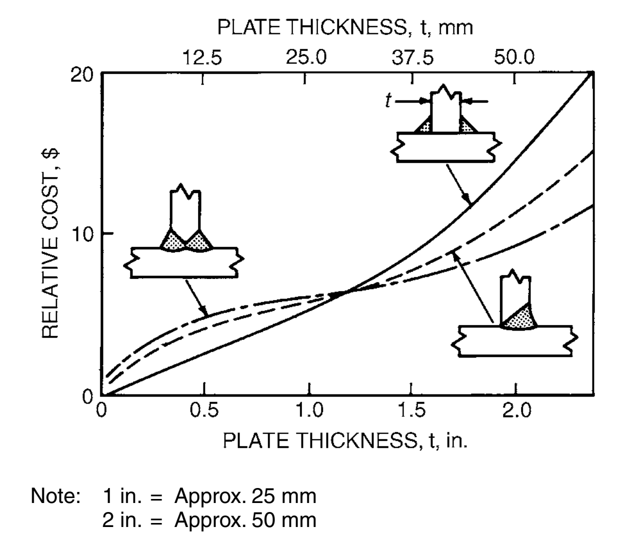


Figure 5.30—Estimated Relative Costs of Fillet and Groove Welds for Various Plate Thicknesses

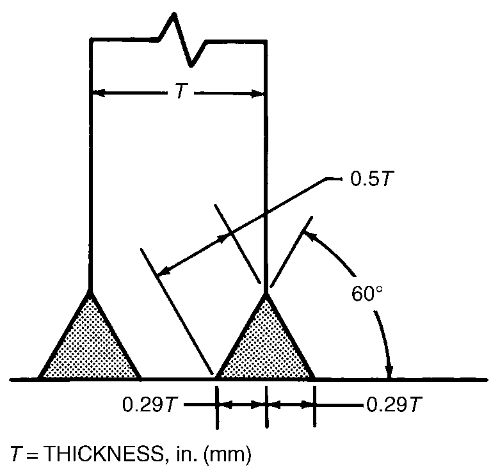


Figure 5.31—Combined Groove and Fillet Welds with Partial Joint Penetration but Capable of Full Strength

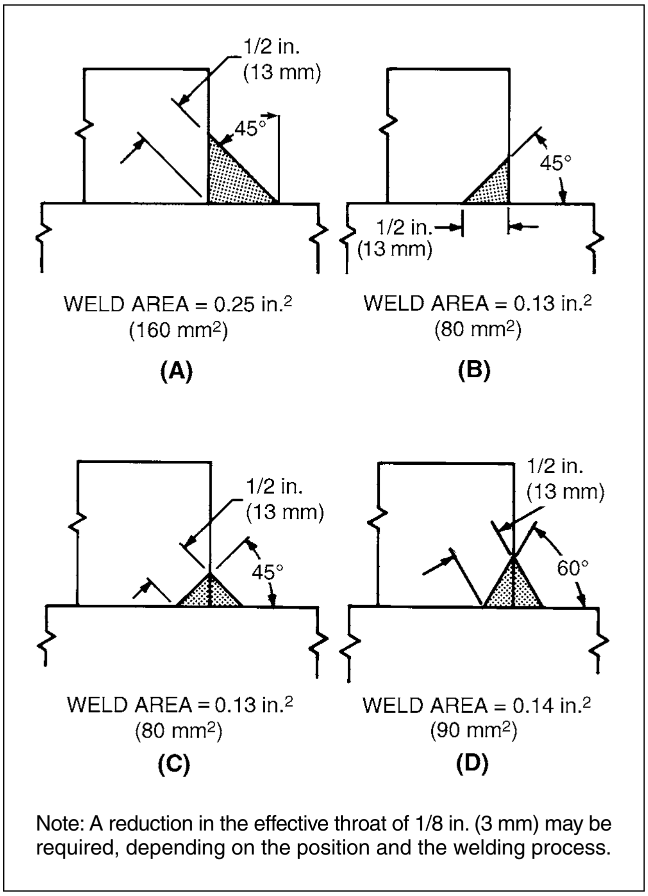


Figure 5.32—Equal Throat T-Joint Welds with Several Joint Configurations and Resulting Weld Deposits: (A) Fillet Weld; (B) Partial Joint Penetration Weld; (C) Partial Joint Penetration Weld with Reinforcing Fillet Weld; and (D) Partial Joint Penetration Weld with Reinforcing Fillet Weld

If a single-bevel-groove weld is combined with a 45° fillet weld, as shown in Figure 5.32(C), the cross-sectional area for the same effective throat is also approximately 50% of the area of the fillet weld in Figure 5.32(A). Here, the bevel depth is shallower than that in the single-bevel-groove weld shown in Figure 5.30(B). A similar weld with a 60° groove angle and an unequal leg fillet but with the same effective throat is depicted in Figure 5.32(D). This weld also requires less weld metal than a fillet weld alone. This joint (with a 60° bevel angle) allows the use of higher welding current and larger electrodes to obtain deep root penetration.

The desired effective throat of a combined groove and fillet weld can be obtained by adjusting the groove dimensions and the leg lengths of the fillet weld. However, consideration must be given to the accessibility of the root of the joint for welding and the potential stress concentration at the fillet weld toe. When a partial joint penetration groove weld is reinforced with a fillet weld, the minimum effective throat is used for design purposes. The effective throat of the combined welds is not the sum of the effective throat of each weld. The combination is treated as a single weld when determining the effective throat.

CORNER JOINTS

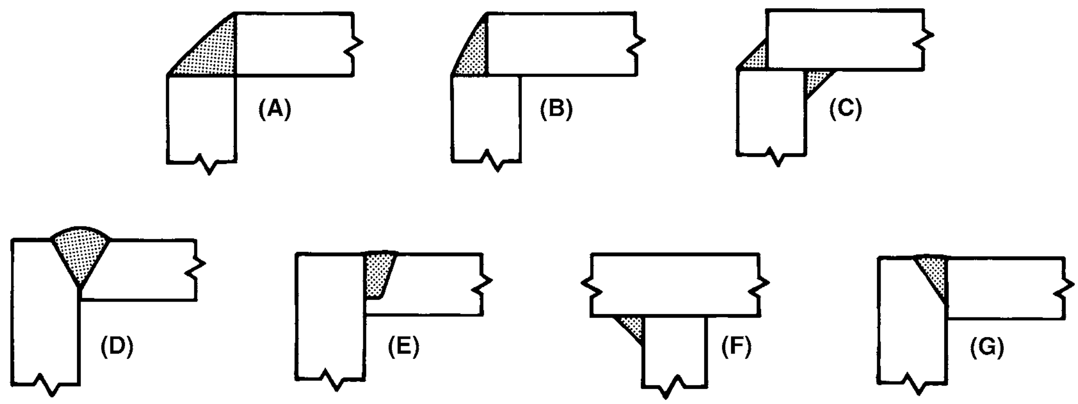
Corner joints are widely used in machine design and box members. Typical corner designs are illustrated in Figure 5.33. The corner-to-corner joint, which is illustrated in Figure 5.33(A), is difficult to position. Thus, it usually requires fixturing. Small electrodes with low welding currents must be used for the first weld pass to avoid excessive melt-through. This joint also requires a large amount of weld metal.

On the other hand, the corner joint shown in Figure 5.33(B) is easy to assemble, needs no backing, and utilizes only about one-half the weld metal required to make the joint shown in Figure 5.33(A). However, this joint has lower strength because the effective throat of the weld is smaller. As illustrated in Figure 5.33(C), two fillet welds, one outside and the other inside, can provide the same total effective throat as with the first design but with one-half the weld metal. However, joint accessibility may be a problem.

For thick sections, a partial joint penetration, the single-V groove weld, which is shown Figure 5.33(D), is often used. This weld requires joint preparation. For deeper joint penetration, a J-groove, depicted in Figure 5.33(E), or a U-groove may be used in preference to a bevel groove. A fillet on the inside corner, such as that shown in Figure 5.33(F), makes a neat and economical corner. This inside fillet weld can be used alone or in combination with any of the outside corner joint configurations shown in Figure 5.33. Joint accessibility may also be an issue for the inside weld.

The size of the weld should always be designed taking into consideration the thickness of the thinner member inasmuch as the joint is only as strong the thinner member. In this way, the weld metal requirements are minimized, resulting in lower costs.

Lamellar tearing at the exposed edges of corner joints in thick steel plates must always be considered during the design phase. Weld joint designs that significantly reduce the through-thickness shrinkage stresses are shown in Figures 5.33(D), (F), and (G). These joint designs exhibit a lower tendency to lamellar tearing than that shown in Figure 5.33(E), in which edge preparation is limited to the base metal not stressed in the through-thickness direction.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-94.

Figure 5.33—Typical Corner Joint Designs

SIZING OF STEEL WELDS

Welds are sized for their ability to withstand static or cyclic loading in accordance with *Structural Welding Code—Steel*, AWS D1.1,[36] to ensure that a soundly welded joint is able to support the applied load for the expected service life. The design strengths of welds for various types of static loading are normally specified in the applicable standard for the job. These are usually based upon a percentage of the tensile or yield strength of the filler or base metal. Similarly, the allowable stress range for cyclic loading is normally specified in the applicable standard for the job.

The following material covers both load and resistance factor design (LRFD) and allowable stress design (ASD). When using LRFD, the loads and corresponding stresses must be calculated using the load factors and combinations presented in Section 2.3 in *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-98.[37] When using ASD, the loads and corresponding stresses must be calculated using the load factors and combinations in Section 2.4 of ASCE 7-98.[38] When the job is one for which this standard is not applicable, the loads and load combinations used should be approximate and consistent with the intent of the standard.

36. See Reference 32.
37. American Society for Civil Engineers, 1998, *Minimum Design Loads for Buildings and Other Structures,* ASCE 7-98, Reston, Virginia: ASCE Publications.
38. See Reference 37.

STATIC LOADING

Examples of design strengths for static loading conditions for steel welds using the AISC load and resistance factor design (LRFD) procedures are presented in Table 5.6. Table 5.7 presents the allowable stresses for static loading which are used when designing with the conventional applied stress design (ASD) procedure. The various types of loading for the welds listed in Table 5.6 and Table 5.7 are illustrated in Figure 5.34.

Complete joint penetration groove welds, illustrated in Figure 5.34(A), (B), (C), and (D), are considered full-strength welds because they are capable of transferring the full strength of the connected elements.

The design strengths in such welds are the same as those in the base metal, provided matching strength weld metal is used. In complete joint penetration groove welds, the mechanical properties of the selected filler metal must at least match those of the base metal. If two base metals of different strengths are welded together, the selected filler metal strength must match or exceed the strength of the weaker base metal.

Partial joint penetration groove welds, illustrated in Figure 5.34(B), (C), (E), and (F), are widely used for the economical welding of thick sections. These welds not only lead to savings in weld metal and welding time, but they also can provide the required joint strength. The minimum weld sizes for prequalified partial joint penetration groove welds are shown in Table 5.8. To avoid cracking in the weld or the heat-affected zone, the minimum weld size should provide adequate process heat input to counteract the quenching effect of the base metal.

Table 5.6
Design Strength for Steel Welds Using AISC Load and Resistance Factor Design (LRFD)

Type of Weld	Stress in the Weld*	Design Strength	Required Filler Metal Strength Level
Complete joint penetration groove welds	Tension normal to the effective area	Same as the base metal	Matching filler metal must be used
	Compression normal to the effective area	Same as the base metal	Filler metal with a strength level equal to or one classification (10 ksi [69 MPa]) less than matching filler metal may be used
	Tension or compression parallel to the axis of the weld	Same as the base metal	Filler metal with a strength level equal to or less than a matching base metal may be used
	Shear on the effective area	0.48 times the nominal tensile, except shear stress on the base metal shall not exceed 0.54 times the yield strength of the base metal	
Partial joint penetration groove welds	Compression normal to the effective area: Joint not designed† to bear in compression	0.75 times the nominal strength† of the filler metal; stress on the base metal shall not exceed 0.90 times the yield strength of the base metal	Filler metal with a strength level equal to or less than a matching filler metal may be used
	Compression normal to the effective area: Joint designed† to bear in compression	Same as base metal	
	Tension or compression parallel to the axis of the weld	Same as the base metal	
	Shear parallel to the axis of the weld	0.45 times the nominal strength of the filler metal, except the tensile stress on the base metal shall not exceed 0.54 times the yield strength of the base metal	
	Tension normal to the effective area	0.48 times the nominal tensile strength of the filler metal, except the tensile strength shall not exceed 0.90 times the yield strength of the base metal	
Fillet welds	Shear on the effective area	0.45 times nominal tensile strength of the filler metal, except the shear stress on the base metal shall not exceed 0.54 times the yield strength of the base metal	Filler metal with a strength level equal to or less than a matching filler metal may be used
	Tension or compression parallel to the axis of the weld	Same as the base metal	
Plug and slot welds	Shear parallel to the faying surfaces (on the effective area)	0.45 nominal tensile strength of filler metal, except shear stress shall not exceed 0.54 times the yield strength of the base metal	Filler metal with a strength level equal to or less than a matching filler metal may be used

*The effective weld area is the effective weld length multiplied by the effective throat.

† Specifications in American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction stipulate design strength to be the same as the base metal without distinction as to whether the joint is milled to bear or not based upon the results of full-size column tests.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Table 2.3; data from American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction, Table J2.5.

Table 5.7
Allowable Stresses in Nontubular Connection Welds (ASD)

Type of Weld	Stress in the Weld*		Allowable Connection Stress†	Required Filler Metal Strength Level‡
Complete joint penetration groove welds	Tension normal to the effective area		Same as the base metal	Matching filler metal must be used
	Compression normal to the effective area		Same as the base metal	Filler metal with a strength level equal to or one classification (10 ksi [69 MPa]) less than matching filler metal may be used
	Tension or compression parallel to the axis of the weld		Same as the base metal	Filler metal with a strength level equal to or less than matching base metal may be used
	Shear on the effective area		0.30 times the nominal tensile, except shear stress on the base metal must not exceed 0.40 times the yield strength of the base metal	
Partial joint penetration groove welds	Compression normal to the effective area	Joint not designed to bear in compression	0.50 times the nominal strength of the filler metal; stress on the base metal must not exceed 0.60 times the yield strength of the base metal	Filler metal with a strength level equal to or less than matching filler metal may be used
		Joint designed to bear in compression	Same as base metal	
	Tension or compression parallel to the axis of the weld§		Same as the base metal	
	Shear parallel to the axis of the weld		0.30 times the nominal strength of the filler metal, except the tensile stress on the base metal must not exceed 0.40 times the yield strength of the base metal	
	Tension normal to the effective area		0.30 times the nominal tensile strength of the filler metal, except the tensile strength must not exceed 0.60 times the yield strength of the base metal	
Fillet welds	Shear on the effective area		0.30 times the nominal tensile strength of the filler metal	Filler metal with a strength level equal to or less than matching filler metal may be used
	Tension or compression parallel to the axis of the weld§		Same as the base metal	
Plug and slot welds	Shear parallel to the faying surfaces (on the effective area)		0.30 nominal tensile strength of filler metal, except shear stress must not exceed 0.40 times the yield strength of the base metal	Filler metal with a strength level equal to or less than a matching filler metal may be used

*The effective area for groove welds is the effective weld length multiplied by the weld size. For fillet welds, the effective area is the effective throat multiplied by the effective length. For plug and spot welds, it is the nominal area of the hole or slot in the plane of the faying surface.
† For cyclic loading, see Table 5.1.
‡ For matching filler metal to base metal strength, refer to American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.
§ Fillet weld and partial joint penetration groove welds joining the component elements of built-up members, such as web-to-flange connections, may be designed without regard to the tensile or compressive stress in these elements parallel to the axis of the welds.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Table 2.3.

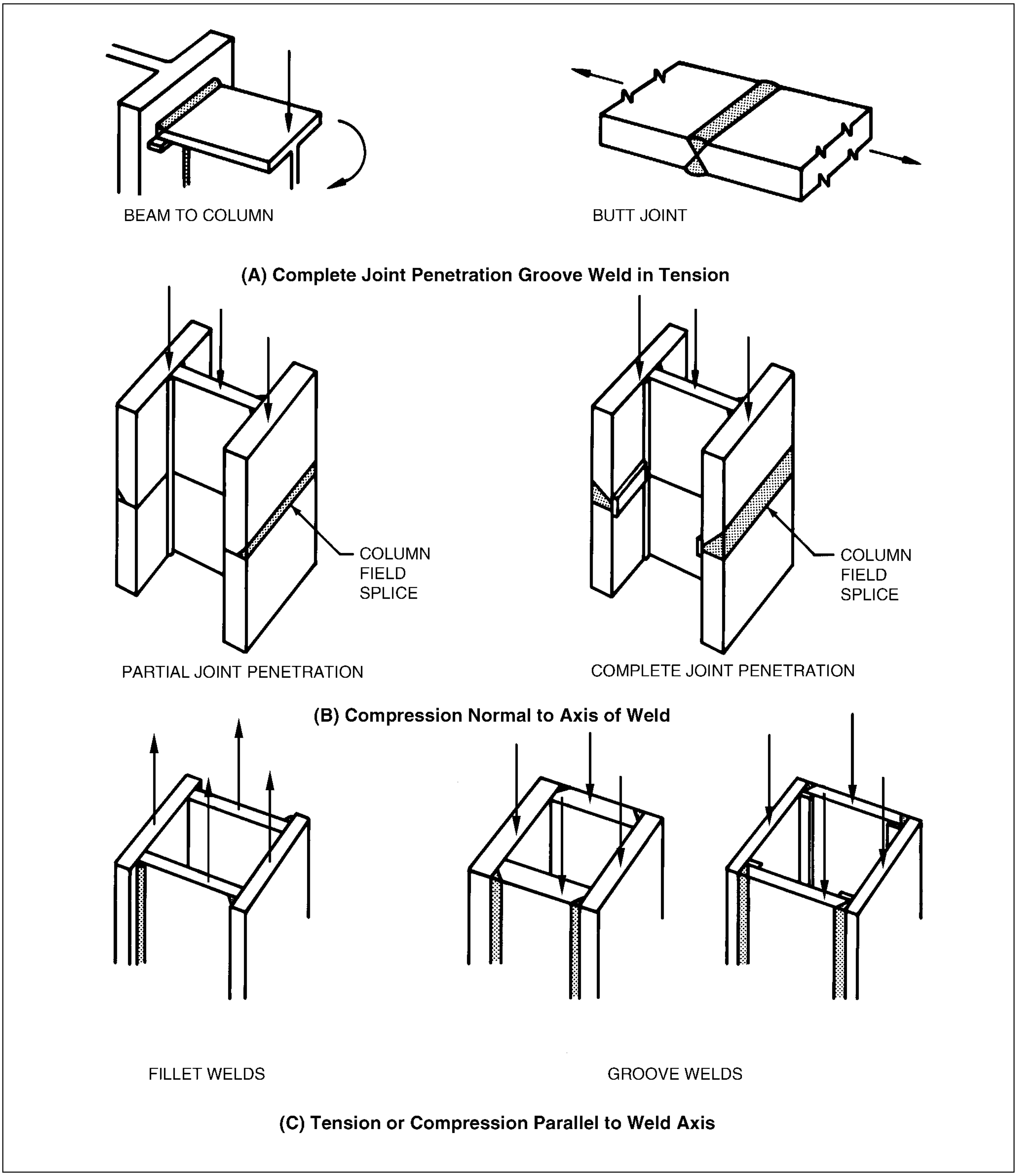


Figure 5.34—Examples of Welds with Various Types of Loading

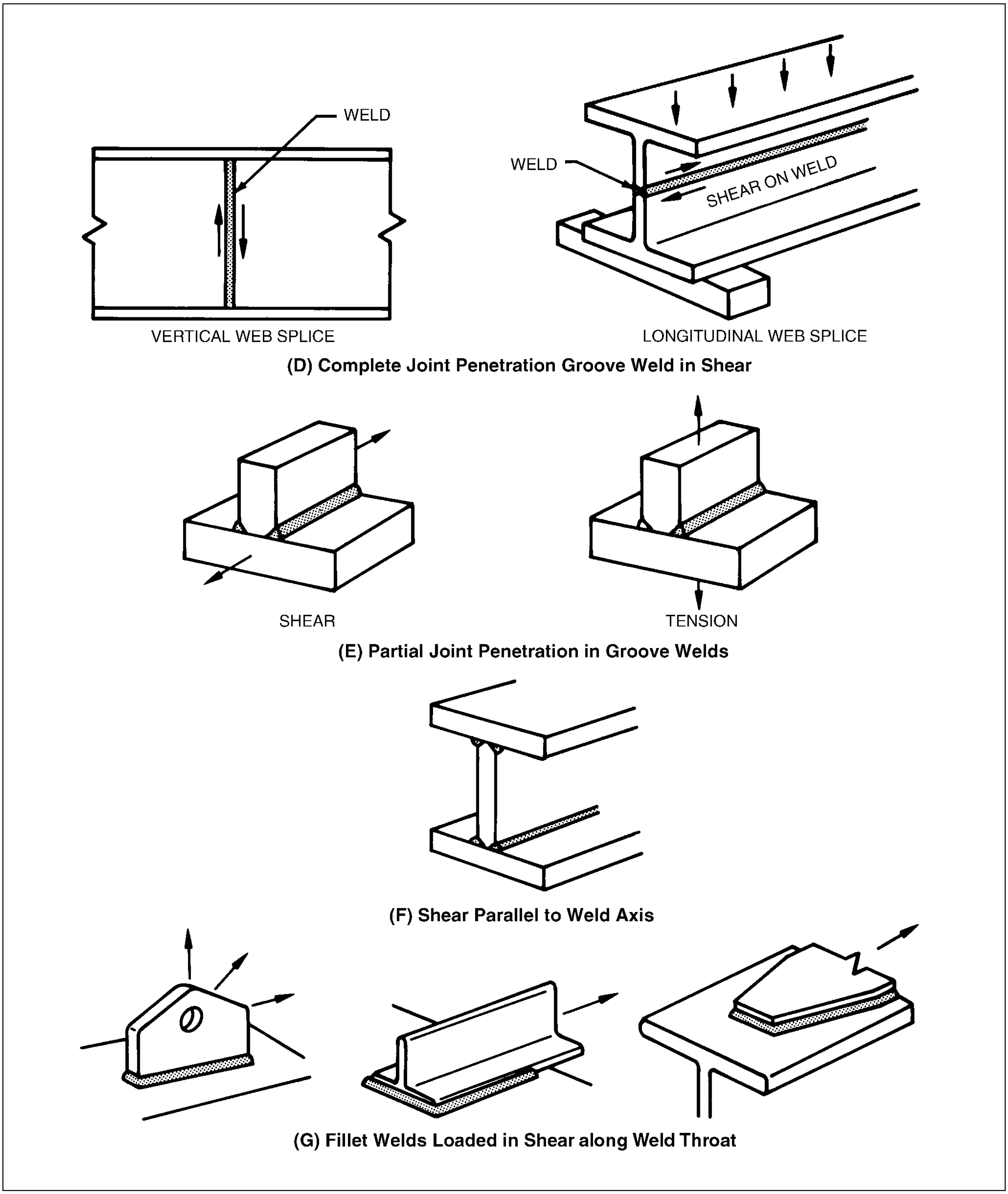


Figure 5.34 (Continued)—Examples of Welds with Various Types of Loading

Table 5.8
Minimum Effective Throat for Partial Joint Penetration Groove Welds in Steel

Thickness of Base Metal*		Maximum Effective Throat†	
in.	mm	in.	mm
1/8 to 3/16	2 to 5	1/16	2
Over 3/16 to 1/4	5 to 6	1/8	3
Over 1/4 to 1/2	6 to 13	3/16	5
Over 1/2 to 3/4	13 to 19	1/4	6
Over 3/4 to 1-1/2	19 to 38	5/16	8
Over 1-1/2 to 2-1/4	38 to 57	3/8	10
Over 2-1/4 to 6	57 to 150	1/2	13
Over 6	150	5/8	16

*Thickness of the thicker section with unequal thickness.
† The effective throat should not exceed the thickness of the thinner part.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Table 3.4.

Various factors should be considered in determining the design strength of the throat of partial joint penetration groove welds. Joint configuration is one factor. The effective throat of a prequalified partial joint penetration groove weld is the depth of the groove when the groove angle is 60° or greater at the root of the weld. For groove angles of less than 60°, the effective throat depends upon the welding process, the welding position, and the groove angle at the root. The provisions of *Structural Welding Code—Steel,* AWS D1.1[39] should be consulted to determine if an allowance for uncertain penetration is required for the conditions of a particular weld.

The LRFD design shear strength for steel weld metal in groove and fillet welds is approximately 45% of the nominal tensile strength of the weld metal ($0.75 \times 0.6\ F_{EXX} = 0.45\ F_{EXX}$, where F_{EXX} equals the minimum specified ultimate tensile strength of the weld metal in ksi [MPa]). Table 5.9 (LRFD) and Table 5.10 (ASD) present the design strength per inch[40] of weld length for various sizes of steel fillet welds of several strength levels. These values are for equal-leg fillet welds in which the effective throat thickness is 70.7% of the weld size.

For example, the design strength, ϕR_n, of a 1/4 in. (6 mm) fillet weld made with an electrode that deposits weld metal of nominal 70,000 psi (480 MPa) minimum tensile strength is determined using LRFD in the following manner:

$$\begin{aligned}\phi R_n &= \phi\left(0.6F_{EXX}\right)A_w \\ &= 0.75\left[0.6\ \times\ 70{,}000\text{ psi }(480\text{ MPa})\right] \\ &\qquad \left[0.707\ \times\ 1/4\text{ in. }(6\text{ mm})\right] \\ &= 5570\text{ lb/in. }(975.4\text{ N/mm})\text{ of weld} \end{aligned} \tag{5.11}$$

where

ϕ = LRFD resistance factor;
R_n = Nominal strength of resistance, lbf (N);
F_{EXX} = Minimum specified weld metal tensile strength, ksi (MPa); and
A_w = Area of shear plane in weld (throat dimension × length), in.^{2} (mm^2).

Use of the minimum fillet weld size is intended to ensure sufficient heat input to reduce the possibility of cracking in either the heat-affected zone or the weld metal, especially in a restrained joint. The minimum size applies if it is greater than the size required for strength.

The minimum fillet weld sizes for structural welds are shown in Table 5.11. Where sections of different thickness are being joined, the minimum fillet weld size is governed by the thicker section if a nonlow-hydrogen electrode is used without preheat. However, if a nonlow-hydrogen electrode is used with the preheat provisions of *Structural Welding Code—Steel*, AWS D1.1[41] or

39. See Reference 32.
40. A footnote in these tables provides information for conversion to SI units.

41. See Reference 32.

Table 5.9
LRFD Design Sheer Strength Per Inch of Length of Steel Equal-Leg Fillet Welds*

Weld Size		Classification Strength Level of the Filler Metal, ksi						
		60	70	80	90	100	110	120
in.	mm	Design Unit Strength, 1000 lb/in.†						
1/16	2	1.19	1.39	1.59	1.79	1.99	2.19	2.39
1/8	3	2.39	2.78	3.18	3.58	3.98	4.37	4.77
3/16	5	3.58	4.18	4.77	5.37	5.97	6.56	7.16
1/4	6	4.77	5.57	6.36	7.16	7.95	8.75	9.54
5/16	8	5.97	6.96	7.95	8.95	9.94	10.9	11.9
3/8	10	7.16	8.35	9.54	10.7	11.9	13.1	14.3
7/16	11	8.35	9.74	11.1	12.5	13.9	15.3	16.7
1/2	13	8.35	9.74	11.1	12.5	13.9	15.3	16.7
5/8	16	9.54	11.1	12.7	14.3	15.9	17.5	19.1
3/4	19	11.9	13.9	15.9	17.9	19.9	21.9	23.9
7/8	22	14.3	16.7	19.1	21.5	23.9	26.2	28.6
1	25	19.1	22.3	25.5	28.6	31.8	35.0	38.2

*Based on American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction. For the ASD allowable, divide the tabular value by 1.5.

† To convert 1000 lb/in. to meganewton per meter (MN/m), multiply the quantity in the table by 0.175.

Table 5.10
ASD Design Strength Per Inch of Length of Steel Fillet Welds*

Weld Size		Classification Strength Level of the Filler Metal, ksi						
		60	70	80	90	100	110	120
in.	mm	Design Unit Strength, 1000 lb/in.†						
1/16	2	0.795	0.928	1.06	1.19	1.33	1.46	1.59
1/8	3	1.59	1.86	2.12	2.39	2.65	2.92	3.18
3/16	5	2.39	2.78	3.18	3.58	3.98	4.37	4.77
1/4	6	3.18	3.71	4.24	4.77	5.30	5.83	6.36
5/16	8	3.98	4.64	5.30	5.97	6.63	7.29	7.95
3/8	10	4.77	5.57	6.36	7.16	7.95	8.75	9.55
7/16	11	5.57	6.50	7.42	8.35	9.28	10.2	11.1
1/2	13	6.36	7.42	8.48	9.55	10.6	11.7	12.7
5/8	16	7.95	9.28	10.6	11.9	13.3	14.6	15.9
3/4	19	9.55	11.1	12.7	14.3	15.9	17.5	19.1
7/8	22	11.1	13.0	14.8	16.7	18.6	20.4	22.3
1	25	12.7	14.8	17.0	19.1	21.2	23.3	25.5

*Based on American Institute of Steel Construction (AISC), 1989, *Manual of Steel Construction: Allowable Stress Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction.

† To convert 1000 lb/in. to MN/m, multiply the quantity in the table by 0.175.

Table 5.11
Minimum Fillet Weld Sizes

Base Metal Thickness (T)*		Minimum Size of Fillet Weld†	
in.	mm	in.	mm
T ≤ 1/4	T ≤ 6	1/8‡	3
1/4 < T ≤ 1/2	6 < T ≤ 12	3/16	5
1/2 < T ≤ 3/4	12 < T ≤ 20	1/4	6
3/4 < T	20 < T	5/16	8

*For nonlow-hydrogen electrodes without preheat calculated in accordance with Section 3.5.2 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, T equals the thickness of the thicker part joined; single-pass welds shall be used. For nonlow-hydrogen electrodes using procedures established to prevent cracking in accordance with Section 3.5.2 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, and for low-hydrogen electrodes, T equals the thickness of the thinner part joined; the single-pass requirement does not apply.
† Except that the weld size need not exceed the thickness of the thinner part joined.
‡ Minimum size for cyclically loaded structures is 3/16 in. (5 mm).

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, D1.1:2000, Miami: American Welding Society, Table 5.8.

low-hydrogen processes are used, the thinner section governs. The weld size need not exceed the thickness of the thinner section unless a larger size is required by the loading conditions.

CYCLIC LOADING

When metals are subjected to cyclic tensile or alternating tensile-compressive stress, they may fail by fatigue. The performance of a weld under a cyclic load is an important consideration in structures and machinery. Specifications relating to fatigue in steel structures include those developed by the American Institute of Steel Construction (AISC), the American Association of State Highway and Transportation Officials (AASHTO), and the American Railway Engineering and Maintenance-of-Way Association (AREMA). The applicable standards published by these organizations are essentially the same as those presented below. Nonetheless, the latest edition of the appropriate standard should be consulted for specific information.

Although sound weld metal may have about the same fatigue strength as the base metal, any change in cross section at a weld lowers the fatigue strength of the member. In the case of a complete joint penetration groove weld, any reinforcement, undercut, incomplete joint penetration, or cracking acts as a notch or stress raiser. Each of these conditions is detrimental to fatigue life. In addition, the very nature of a fillet weld transverse to the stress field provides an abrupt change in section that may limit fatigue life. The weld heat-affected zone can also act as a stress raiser due to the metallurgical structure.

The fatigue stress provisions in *Structural Welding Code—Steel,* AWS D1.1:2000,[42] are presented in Table 5.12 and illustrated in Figure 5.35. Curves for the allowable stress ranges[43] for each stress category are plotted in Figure 5.36 for redundant[44] structures.

The allowable stress ranges presented in Figure 5.36 are independent of yield strength; therefore, they apply equally to all structural steels. When fatigue conditions exist, the anticipated cyclically applied loads, the number of cycles, and the desired service life must be given. The designer then selects the materials and details to accommodate the design conditions for each member and situation (see Table 5.12 and Figure 5.35). The designer then calculates the maximum stress in each member to ensure that it does not exceed the allowable stress for the static condition. If the calculated stresses under cyclic conditions exceed the allowable stress under static conditions, the member sections must be increased to bring the stresses within the allowable stress.

Partial joint penetration groove welds are not normally used in fatigue applications. However, their response to fatigue stresses is similar to that of fillet welds.

42. See Reference 33.
43. A stress range is the magnitude of the change in stress that occurs with the application or removal of the cyclic load that causes tensile stress or a reversal of stress. Loads that cause only changes in the magnitude of compressive stress do not cause fatigue.
44. A redundant structure provides an alternate load path in the event of failure of a member or members.

Table 5.12
Fatigue Stress Provisions—Tension or Reversal Stresses* (Nontubular Members)

General Condition	Situation	Stress Category (see Figure 5.35)	Example (see Figure 5.35)
Plain material	Base metal with rolled or cleaned surfaces. Oxygen-cut edges with ANSI smoothness of 1000 or less.	A	1, 2
Built-up members	Base metal and weld metal in members without attachments, built up of plates or shapes connected by continuous, complete, or partial joint penetration groove welds or by continuous fillet welds parallel to the direction of applied stress.	B	3, 4, 5, 7
	Calculated flexural stress at toe of transverse stiffener welds on girder webs or flanges.	C	6
	Base metal at end of partial length welded cover plates having square or tapered ends, with or without welds across the ends.	E	7
Groove welds	Base metal and weld metal at complete joint penetration, groove-welded splices of milled and welded sections having similar profiles when welds are ground[1] and weld soundness established by nondestructive testing.[2]	B	8, 9
	Base metal and weld metal in or adjacent to complete joint penetration, groove-welded splices at transitions in width or thickness, with welds ground[1] to provide slopes no steeper than 1 in. to 2-1/2 in. (25 mm to 64 mm)[3] for yield strength less than 90 ksi (620 MPa) and a radius[8] of $R \geq 2$ ft (0.6 m) for yield strength $\geq$ 90 ksi (620 MPa), and weld soundness established by nondestructive examination.[2]	B	10, 11a, 11b

General Condition	Situation	Longitudinal loading	Transverse loading[4]: Materials having equal or unequal thickness, sloped;[6] web connections excluded	Transverse loading[4]: Materials having equal thickness, not ground; web connections excluded	Transverse loading[4]: Materials having unequal thickness, not sloped or ground, including web connections	Example (see Figure 5.35)
Groove-welded connections	Base metal at details of any length attached by groove welds subjected to transverse or longitudinal loading, or both, when weld soundness transverse to the direction of stress is established by nondestructive testing[2] and the detail embodies a transition radius, R, with the weld termination ground[1] when:					
	(a) $R \geq 24$ in. (600 mm)	B	B	C	E	13
	(b) 24 in. (600 mm) $> R \geq 6$ in. (150 mm)	C	C	C	E	13
	(c) 6 in. (150 mm) $> R \geq 2$ in. (50 mm)	D	D	D	E	13
	(d) 2 in. (50 mm) $> R \geq 0$[7]	E	E	E	E	12, 13

*Except as noted for fillet and stud welds.

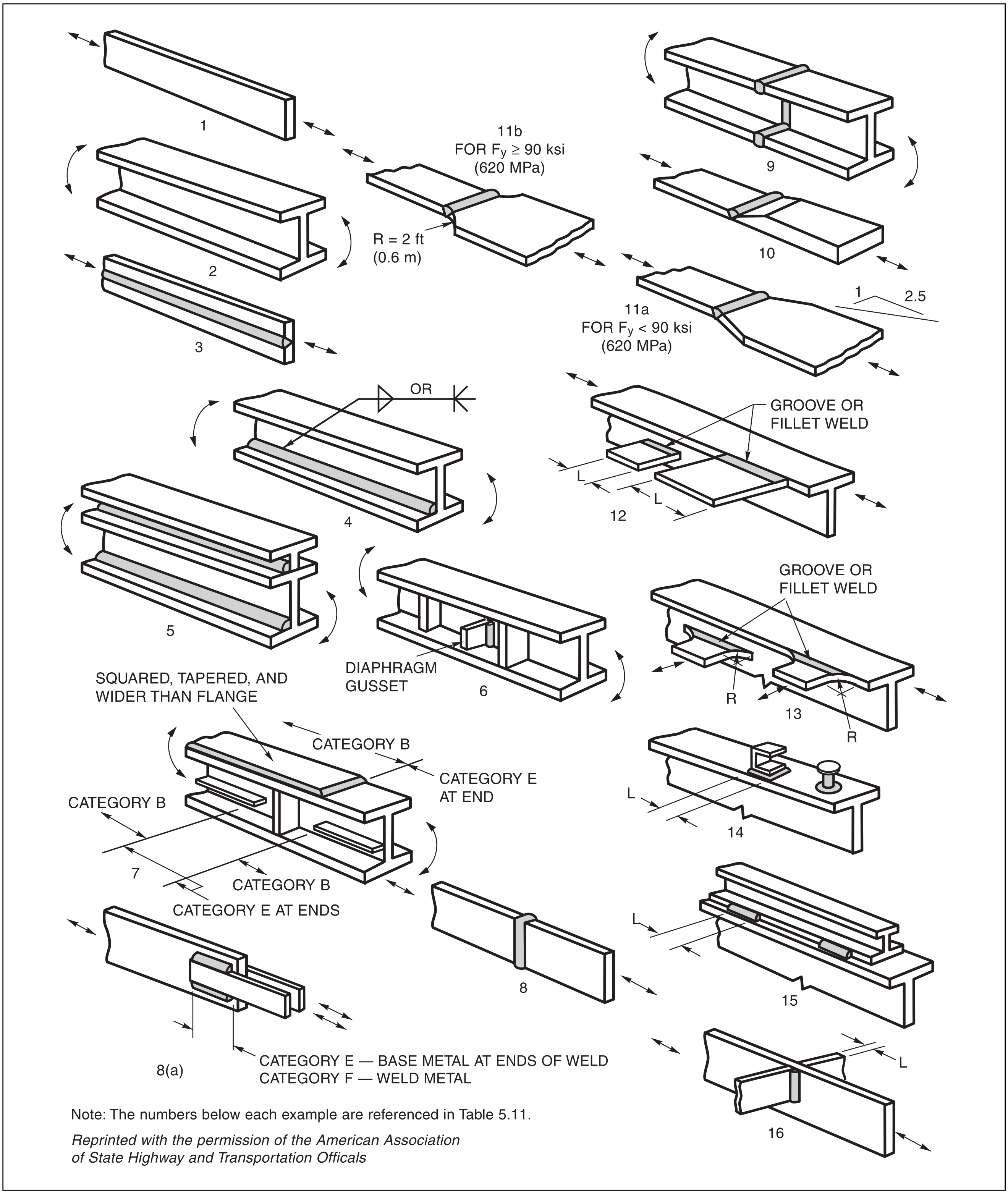
(Continued)

Table 5.12 (Continued)
Fatigue Stress Provisions—Tension or Reversal Stresses* (Nontubular Members)

General Condition	Situation	Stress Category (see Figure 5.35)	Example (see Figure 5.35)
Groove welds	Base metal and weld metal in or adjacent to complete joint penetration groove-welded splices either not requiring transition or when required with transitions having slopes no greater than 1 in. to 2-1/2 in. (25 mm to 64 mm)[3] for yield strength less than 90 ksi (620 MPa) and a radius[8] of $R \geq 2$ ft (0.6 m) for yield strength ≥ 90 ksi (620 MPa), and when in either case reinforcement is not removed and weld soundness is established by nondestructive testing.[2]	C	8, 9, 10, 11a, 11b
Groove- or fillet-welded connections	Base metal at details attached by groove or fillet welds subject to longitudinal loading where the details embody a transition radius, R, less than 2 in.[7] (50 mm) and when the detail length, L, parallel to the line of stress is:		
	(a) < 2 in. (50 mm)	C	12, 14, 15, 16
	(b) 2 in. (50 mm) ≤ L < 4 in. (100 mm)	D	12
	(c) L ≥ 4 in. (100 mm)	E	12
Fillet-welded connections	Base metal at details attached by fillet welds parallel to the direction of stress regardless of length when the detail embodies a transition radius, R, 2 in. (50 mm) or greater and with the weld termination ground.[1]		
	(a) When $R \geq 24$ in. (600 mm)	B[5]	13
	(b) When 24 in. (600 mm) > $R \geq 6$ in. (150 mm)	C[5]	13
	(c) When 6 in. (150 mm) > $R \geq 2$ in. (50 mm)	D[5]	13
Fillet welds	Shear stress on throat of fillet welds	F	8a
	Base metal at intermittent welds attaching transverse stiffeners and stud-type shear connectors.	C	7, 14
	Base metal at intermittent welds attaching longitudinal stiffeners.	E	—
Stud welds	Shear stress on nominal shear area of Type-B shear connectors.	F	14
Plug and slot welds	Base metal adjacent to or connected by plug or slot welds.	E	—

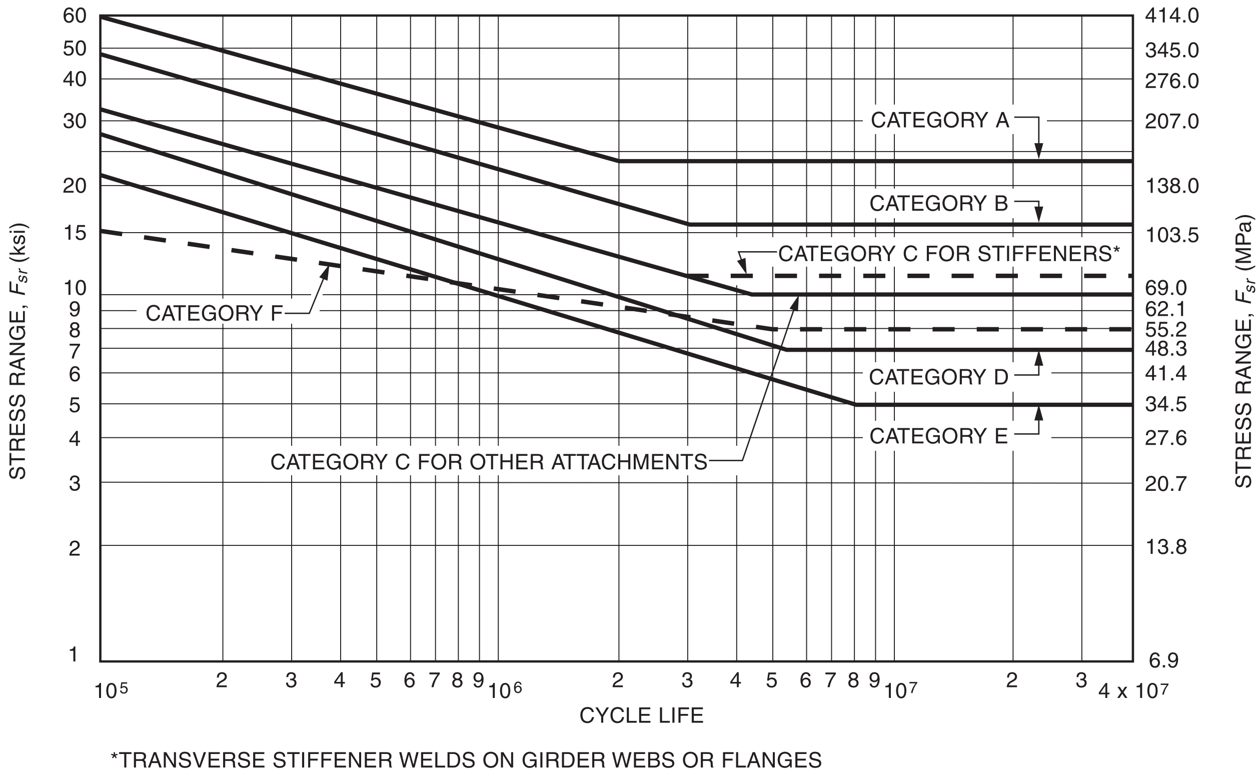
Notes:
[1] Finished according to Sections 5.24.4.1 and 5.24.4.2 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.
[2] Either RT or UT to meet quality requirements of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Sections 6.12.2 or 6.13.2 for welds subject to tensile stress.
[3] Sloped as required by Section 2.29.1 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.
[4] Applicable only to complete joint penetration groove welds.
[5] Shear stress on throat of weld (loading through the weld in any direction) is governed by Category F.
[6] Slopes similar to those required by Note 3 are mandatory for categories listed. If slopes are not obtainable, Category E must be used.
[7] Radii less than 2 in. (50 mm) need not be ground.
[8] Radii used as required by Section 2.29.3 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.
*Except as noted for fillet and stud welds.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Table 2.4.



Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 2.8.

Figure 5.35—Examples of Various Fatigue Categories



Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figures 2.9 and 2.10.

Figure 5.36—Design Stress Range Curves for Categories A to F: Redundant Structures

DESIGN FOR RIGIDITY OR STIFFNESS

In machine design work, the primary design requirement for many members is rigidity. The members having these requirements are often thick sections that provide for the movement under load to be within close tolerances. The resulting stresses in the members are very low. Often, the actual stress in a welded machine base or frame may be on the order of one-tenth or less of the design strength. In these cases, the weld sizes need to be designed for rigidity rather than load conditions.

A very practical method involves designing the weld size to carry one-third to one-half of the strength of the thinner member being joined. In this way, if the base metal is stressed to one-third to one-half of the design strength, the weld will be strong enough to carry the load. Most rigid designs are stressed below these values. It should be noted, however, that a reduction in weld size below one-third of the normal full-strength size might produce a weld that is too small in appearance for general acceptance.

MATCHING WELD METAL

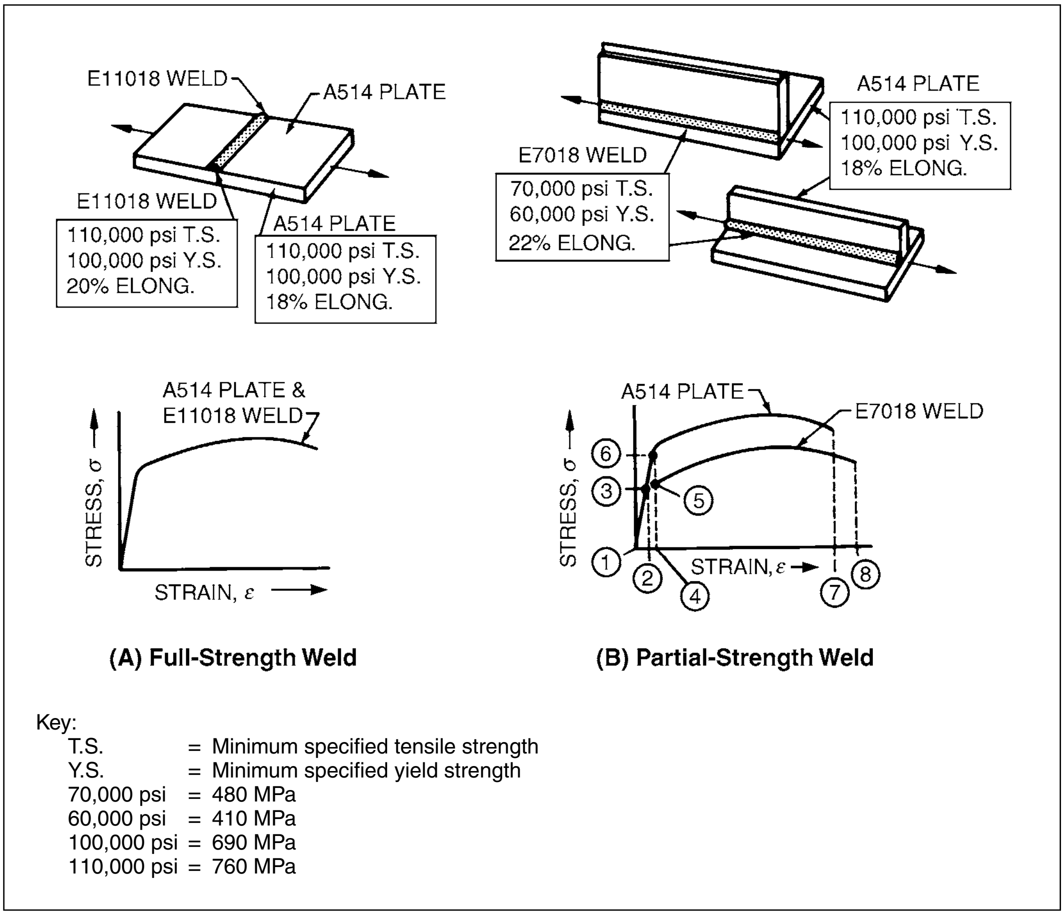
When a full-strength primary weld is required, a filler metal with mechanical properties that match those of the base metal must be selected. Generally, it is unnecessary for the compositions of the weld metal and base metal to be exactly alike. In fact, in many instances, they are dissimilar. For low-alloy chromium-molybdenum and stainless steels as well as for most nonferrous alloys, the compositions of the weld metal are similar to those of the base metals. For materials strengthened by heat treatment, the manufacturer's recommendations should be followed to avoid the degradation of the mechanical properties by the heat or welding.

When working with high-strength steels, full-strength welds should not be used unless they are required. High-strength steel requires preheat and special welding procedures because of its propensity for weld cracking, especially if the joint is restrained.

Some welds are nonstructural; that is, rather than providing for the direct transfer of forces, they serve an ancillary purpose, such as to hold the parts together to form a built-up member. In most cases, the stresses on these secondary welds are low. Thus, they can be made with weld metal that is lower in strength than base metal. Weld metal with a minimum tensile strength of 70,000 psi to 90,000 psi (480 MPa to 620 MPa) is preferred because the likelihood of cracking is lower than when using matching weld metal. In any case, the weld must be sized to provide a joint of sufficient strength.

A comparison of the behaviors of full-strength and partial-strength welds made in quenched-and-tempered ASTM A514 steel is shown in Figure 5.37. The full-strength weld is transverse to the tensile load, whereas the partial-strength weld is parallel to the tensile load. As shown in Figure 5.37(A), the plate, which has a tensile strength of 110,000 psi (760 MPa), is welded with an E11018 covered electrode to produce a full-strength weld. When the stress is parallel to the weld axis, as shown in Figure 5.37(B), a weld made with an E7018 covered electrode (70,000 psi [480 MPa] minimum tensile strength) is adequate as long as it successfully transmits any shear load from one member to the other.

In full-strength welded joints, both the plate and the weld metal have equivalent strengths. Their behavior under load is shown by the stress-strain curve in Figure



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-123.

Figure 5.37—Stress versus Strain Characteristics of Full- and Partial-Strength Welds

5.37(A). If a transversely loaded test weld were pulled in tension, it is likely that the failure would take place in the plate because of its slightly lower strength.

In lower-strength weld joints loaded axially, such as that illustrated in Figure 5.37(B), both the plate and the weld would be strained together. As the member is loaded, the strain increases from 1 to 2 on the stress-strain plot with a corresponding increase in the stress in both the plate and weld from 1 to 3. At this point, the E7018 weld metal has reached its yield strength. Upon further loading, the strain is increased to 4. The weld metal is stressed beyond its yield strength at 5, at which point it flows plastically. However, the plastic deformation is controlled and limited by the base material, which is still elastic. On the other hand, the stress in the plate is still below its yield strength at 6. With further loading, the strain will reach 7, at which point the ductility of the plate will be exhausted. The plate will fail first because the weld metal has greater ductility. The weld will not fail until its unit strain reaches 8.

Figure 5.37 illustrates the fact that the 70,000 psi (480 MPa) weld has sufficient strength to carry an axial load because it carries only a small portion of the total axial load on the weldment. If a weld is to transmit the total load, it has to be as strong as the base metal.

SKEWED FILLET WELDS

A special condition exists when members come together at an angle other than 90° and fillet welds are to be used to make the connection. Ordinary specifications for the weld leg at some joint angles could result in an excessive waste of weld metal along with difficulty in depositing the weld on the acute side of the joint.

Figure 5.38 examines the relationships between the dihedral angle, Ψ, the weld size, b, and the effective throat, t, of skewed fillet welds. The accompanying equations are used to determine the proper effective throat for each weld to allow for the deposit of a minimum area, A_t, of weld metal in the joint. Weld sizes b_1 and b_2 can be determined for the respective effective throats. The reader is advised to refer to *Structural Welding Code—Steel,* AWS D1.1,[45] for information concerning welds in angles less than 60° for Z-loss factors on the effective throat.

TREATING A WELD AS A LINE

For the sake of convenience, when the total length of weld in a connection is large compared to its effective throat, the weld can be assumed to be a line having a definite length and configuration rather than an area. The proper size of weld required for adequate strength can be determined using this concept. The welded connection is considered as a single line having the same outline as the connection area. This is shown in Figure 5.39, where b denotes width and d represents depth. Thus, the welded connection has length, not effective area. In this way, the problem becomes one of determining the force per unit length on the weld instead of the stress on a weld, which cannot be established until the weld size is known.

When the weld is treated as a line, the property of a welded connection can be substituted in the standard design equation used for the particular type of load, as shown in Table 5.13. The force per unit length on the weld can then be calculated with the appropriate modified equation.

Problems involving bending or twisting loads may be satisfactorily and conservatively handled by treating the unit loads as vectors and adding the vector. The actual strength of welded connections in which the external load does not pass through the shear center of the weld requires the use of a more complex approach. This method recognizes that when an eccentric load is applied, both relative rotation and translation between the welded parts occur. The actual center of rotation is not about the center of gravity of the weld group. Instead, it is about a center that is dependent upon the relative magnitude of the shear and moment reactions, weld geometry, and deformations of obliquely loaded incremental lengths of weld. The geometrical properties of common joint configurations can be determined using the equations shown in Table 5.14.

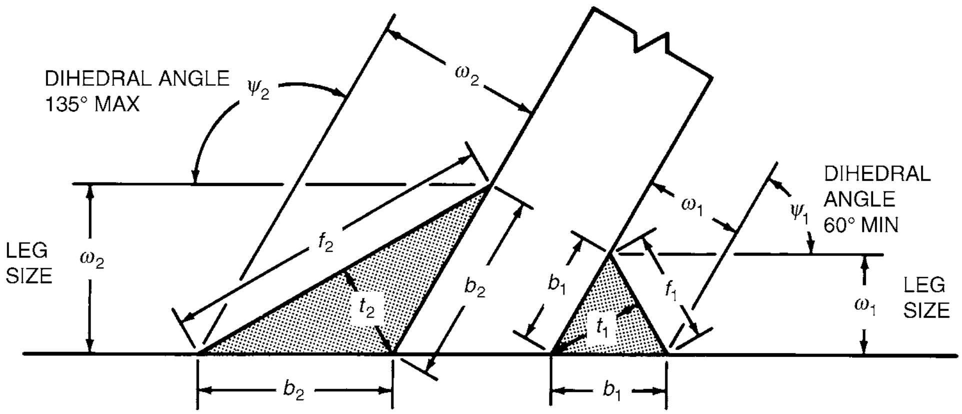
For a given connection, two dimensions are needed—the length of the horizontal weld, b, and the length of the vertical weld, d. The section modulus, S_W, is used for welds subjected to bending loads, while the polar moment of inertia of a line weld, J_w, and distance, c, are used for torsional loads. Section moduli are given for the maximum force at the top and bottom or right and left portions of the welded connections. For the unsymmetrical connections shown in Table 5.13, the maximum bending force is at the bottom of the connection.

If more than one force is applied to the weld, the unit forces are combined vectorially. All unit forces that are combined must be vectored at a common location on the welded joint. Weld size is found by dividing the resulting unit force on the weld by the design strength of the type of weld used. The steps used in applying this method to any welded construction are presented below:

Step 1. Find the position on the welded connection where the combined unit forces are at the maximum. More than one combination deserving consideration may be present;

Step 2. Find the value of each of the unit forces on the welded connection at this position;

45. See Reference 32.



For Each Weld:

$$t = \frac{\omega}{2\sin\left(\frac{\psi}{2}\right)} \text{ or } \omega = 2\,t\sin\left(\frac{\psi}{2}\right)$$

$$f = \frac{\omega}{\cos\left(\frac{\psi}{2}\right)} = 2\,t\,\tan\left(\frac{\psi}{2}\right)$$

$$b = \frac{t}{\cos\left(\frac{\psi}{2}\right)}$$

$$A = \frac{\omega^2}{4\sin\left(\frac{\psi}{2}\right)\cos\left(\frac{\psi}{2}\right)} = t^2\tan\left(\frac{\psi}{2}\right)$$

If $b_1 = b_2$, then for $t = t_1 + t_2$:

$$t_1 = t\,\frac{\cos\left(\frac{\psi_2}{2}\right)}{\cos\left(\frac{\psi_1}{2}\right)+\cos\left(\frac{\psi_2}{2}\right)} \qquad t_2 = t\,\frac{\cos\left(\frac{\psi_2}{2}\right)}{\cos\left(\frac{\psi_1}{2}\right)+\cos\left(\frac{\psi_2}{2}\right)}$$

For Minimum Total Weld Metal:

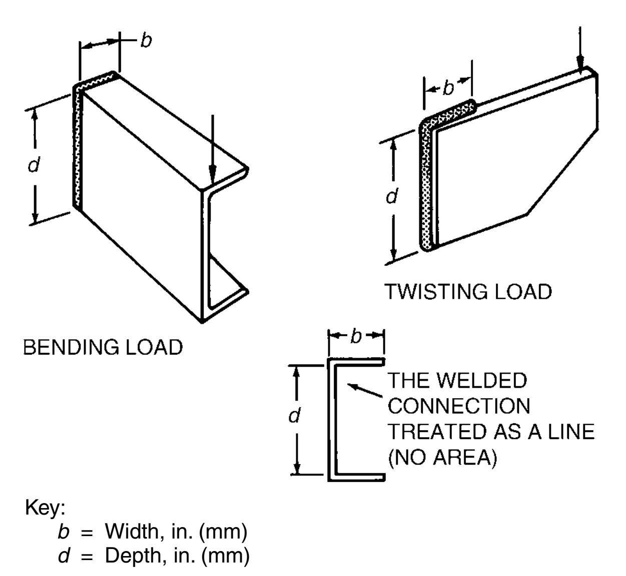
$$t_1 = \frac{t}{1+\tan^2\left(\frac{\psi_1}{2}\right)} \qquad t_2 = \frac{t}{1+\tan^2\left(\frac{\psi_2}{2}\right)}$$

$$A_t = \frac{t^2\tan\left(\frac{\psi_1}{2}\right)}{1+\tan^2\left(\frac{\psi_1}{2}\right)}$$

Key:

t = Theoretical weld throat dimension, in. (mm)
ω = Distance from member to a parallel line extended from the bottom weld toe, in. (mm)
ψ = Dihedral angle, degrees
f = Weld face size, in. (mm)
b = Weld leg size, in. (mm)
A = Weld cross-sectional area, in.^{2} (mm^2)
b_1 = Leg size of Weld 1, in. (mm)
b_2 = Leg size of Weld 2, in. (mm)
t_1 = Throat dimension of Weld 1, in. (mm)
t_2 = Throat dimension of Weld 2, in. (mm)
A_t = Total weld cross-sectional area, in.^{2} (mm^2)

Figure 5.38—Equations for the Analysis of Skewed T-Joints



Source: Adapted from Blodgett, O. W., 1966, *Design of Welded Structures,* Cleveland: The James F. Lincoln Arc Welding Foundation, Figure 14.

Figure 5.39—Treating a Weld as a Line

Step 3. Select the appropriate equation from Table 5.13 to find the unit force on the weld;
Step 4. Use Table 5.13 to find the appropriate properties of the welded connection treated as a line;
Step 5. Combine vectorially all of the unit forces acting on the weld; and
Step 6. Determine the required effective throat size by dividing the total unit force by the allowable stress in the weld.

The following example illustrates the application of these steps in calculating the size of a weld considered as a line. Assume that a bracket supporting an eccentric load of 18,000 lb (80 000 N) is to be fillet welded to the flange of a vertical column, as shown in Figure 5.40. The procedures for determining the design strength of various eccentrically loaded welded connections used in structural steel construction are provided in the *Manual of Steel Construction: Load and Resistance Factor Design.*[46]

In Step 1, the point of maximum combined unit forces is determined to be at the right ends of the top and bottom horizontal welds.

In Step 2, the torsional force caused by the eccentric loading is divided into horizontal (f_h) and vertical (f_v) components. The distance from the center of gravity to the point of combined stress, C, is calculated from the equation for C in Table 5.13 for this general shape of connection (the fourth configuration), as follows:

$$C = \left[C_{YR}^2 + \left(\frac{d}{2}\right)^2\right]^{1/2} \tag{5.12}$$

where

C = Distance from the center of gravity to the point of combined stress, in. (mm);
C_{YR} = Horizontal distance from the center of gravity to the point of combined stress, which equals

$$\frac{b(b+d)}{2b+d} = \frac{5(5+10)}{2(5)+10} = \frac{75}{20} = 3.75 \text{ in. (95 mm)};$$

d = Length of the vertical weld, in. (mm); and
b = Length of horizontal weld, in. (mm).

The polar moment of inertia is then determined by the following:

$$J_w = \frac{b^3}{3}\frac{(b+2d)}{2b+d} + \frac{d_2}{12}(6b+d)$$

$$= \frac{5^3}{3}\frac{(5+20)}{10+10} + \frac{10^2}{12}(30+10)$$

$$= 385 \text{ in.}^3 \left(6.3\times10^6 \text{ mm}^3\right) \tag{5.13}$$

where

J_w = Polar moment of inertia of a line weld, in.^{4} (mm^4);
b = Length of horizontal weld, in. (mm); and
d = Length of vertical weld, in. (mm).

The horizontal component of twisting, f_h, is determined from the Equation (4) in Table 5.12, as follows:

$$f_h = \frac{T(d/2)}{J_w} = \frac{(180{,}000)(10/2)}{385}$$

$$= 2340 \text{ lb/in. (410 N/mm)} \tag{5.14}$$

where

f_h = Horizontal force component due to twisting, lb (N);
T = Torque (= 18,000 × 10 = 180,000 in. lb (31.5 kN mm);

46. See Reference 27.

Table 5.13
Equations for the Calculation of Force per Unit Length

Type of Loading	Standard Equations for Unit Stress	Equations for Force per Unit Length	
Tension or compression	$\sigma = \dfrac{P}{A}$ ksi (MPa)	$f = \dfrac{P}{L_w}$ lb / in. (N / mm)	(1)
Vertical shear	$\tau = \dfrac{V}{A}$ ksi (MPa)	$f = \dfrac{V}{L_w}$ in. / in. (N / mm)	(2)
Bending	$\sigma = \dfrac{M}{S} = \dfrac{Mc}{I}$ ksi (MPa)	$f = \dfrac{M}{S_w} = \dfrac{Mc}{Iw}$ lb / in. (N / mm)	(3)
Torsion	$\tau = \dfrac{Tc}{J}$ ksi (MPa)	$f = \dfrac{Tc}{J_w}$ lb / in. (N / mm)	(4)

Key:
- σ = Normal stress, ksi (MPa)
- P = Applied force, kips (kN)
- A = Total area of the cross section, in.^{2} (mm^2)
- f = Force per unit, kips (kN)
- L_w = Total length of the line weld, in. (mm)
- τ = Shear stress, ksi (MPa)
- V = Vertical shear load, kips (kN)
- M = Bending moment, kips in. (kN mm)
- S = Section modulus of an area, in.^{4} (mm^4)
- I = Moment of inertia, in.^{4} (mm^4)
- S_w = Section modulus of a line weld, in.^{4} (mm^4)
- I_w = Moment of inertia of a line weld, in.^{4}/in. (mm^4/mm)
- T = Torque on the weld joint, kips in. (kN mm)
- c = Distance from the neutral axis to the extreme fibers of a line weld, in. (mm)
- J = Polar moment of inertia of an area, in.^{4} (mm^4)
- J_w = Polar moment inertia of a line weld, in.^{4}/in. (mm^4/mm)

d = Length of vertical weld, in (mm); and
J_w = Polar moment of inertia of a line weld, in.^{4} (mm^4).

The vertical twisting component is determined from Equation (1) in Table 5.12, as follows:

$$f_v = \frac{TC_{YR}}{J_w} = \frac{(180{,}000)(3.75)}{385}$$

$$= 1750 \text{ lb/in. } (306 \text{ N/mm}) \qquad (5.15)$$

where

f_v = Vertical twisting force component, lbf (N);
T = Torque, in. lb (kN mm);
C_{YR} = Horizontal distance from the center of gravity to the point of combined stress, which equals

$$\frac{b(b+d)}{2b+d} = \frac{5(5+10)}{2(5)+10} = \frac{75}{20} = 3.75 \text{ in. } (95 \text{ mm});$$

J_w = Polar moment of inertia of a line weld, in.^{4} (mm^4).

The vertical shear force is determined from Equation (1) in Table 5.12, as follows:

$$f_s = \frac{P}{L_w} = \frac{180{,}000}{20} = 90 \text{ lb/in. } (158 \text{ N/mm}) \qquad (5.16)$$

where

f_s = Vertical shear force, lb (N);
F = Applied load, lbf (N); and
L_w = Total length of the weld, in. (mm).

In Step 3, the resultant force is determined, as follows:

$$f_r = \left[f_h^2 + (f_v + f_s)^2\right]^{1/2}$$

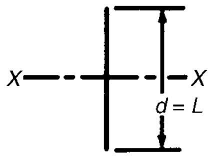
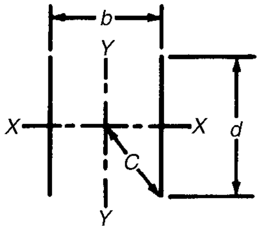
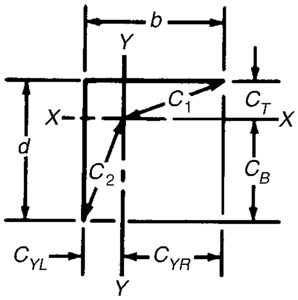
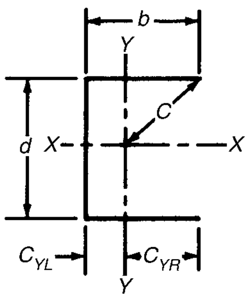
$$= \left[(2340)^2 + (1750 + 900)^2\right]^{1/2}$$

$$= 3540 \text{ lb/in. } (620 \text{ N/mm}) \qquad (5.17)$$

where

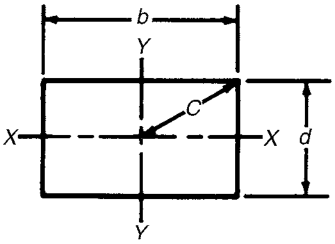
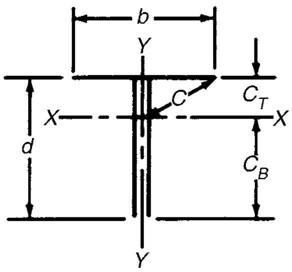
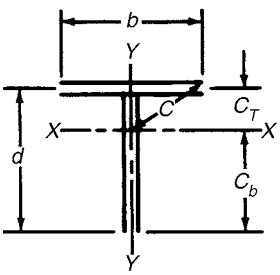
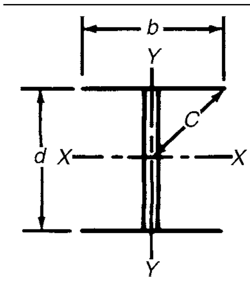
f_r = Resultant force, lbf (N);
f_h = Horizontal force component due to twisting, lbf (N);
f_v = Vertical twisting force component, lbf (N); and
f_s = Vertical shear force, lb (N).

Table 5.14
Properties of Welded Construction Treated as a Line

	$I_X = \frac{d^3}{12}$	$S_X = \frac{d^2}{6}$	
 $L = 2d$	$I_X = \frac{d^3}{6}$ $I_Y = \frac{b^2 d}{2}$	$S_X = \frac{d^2}{3}$ $S_Y = bd$	$J_W = \frac{d}{6}(3b^2 + d^2)$ $C = \frac{(b^2 + d^2)^{1/2}}{2}$
 $L = b + d$	$I_X = \frac{d^3}{12}\left(\frac{4b + d}{b + d}\right)$ $I_Y = \frac{b^3}{12}\left(\frac{b + 4d}{b + d}\right)$ $J_W = \frac{b^3 + d^3}{12} + \frac{bd(b^2 + d^2)}{4(b + d)}$ $C_T = \frac{d^2}{2(b + d)}$ $C_{YL} = \frac{b^2}{2(b + d)}$	$S_{XT} = \frac{d}{6}(4b + d)$ $S_{YL} = \frac{b}{6}(b + 4d)$ $C_B = \frac{d}{2}\left(\frac{2b + d}{b + d}\right)$ $C_{YR} = \frac{b}{2}\left(\frac{b + 2d}{b + d}\right)$	$S_{XB} = \frac{d^2}{6}\left(\frac{4b + d}{2b + d}\right)$ $S_{YR} = \frac{b^2}{6}\left(\frac{b + 4d}{2d + b}\right)$ $C_1 = (C_T{}^2 + C_{YR}{}^2)^{1/2}$ $C_2 = (C_B{}^2 + C_{YL}{}^2)^{1/2}$
 $L = 2b + d$	$I_X = \frac{d^2}{12}(6b + d)$ $I_Y = \frac{b^3}{3}\left(\frac{b + 2d}{2b + d}\right)$ $C_{YL} = \frac{b^2}{2b + d}$ $C = \left[C_{YR}{}^2 + \left(\frac{d}{2}\right)^2\right]^{1/2}$	$S_X = \frac{d}{6}(6b + d)$ $S_{YL} = \frac{b}{3}(b = 2d)$ $C_{YR} = \frac{b(b + d)}{2b + d}$ $J_W = \frac{b^3}{3}\left(\frac{b + 2d}{2b + d}\right) + \frac{d^2}{12}(6b + d)$	 $S_{YR} = \frac{b^2}{3}\left(\frac{b + 2d}{b + d}\right)$

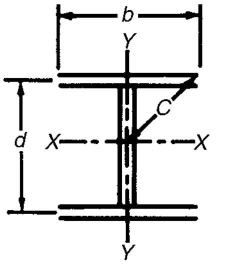
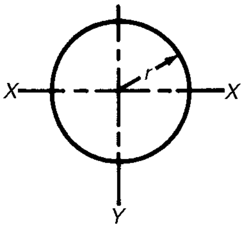
(Continued)

Table 5.14 (Continued)
Properties of Welded Construction Treated as a Line

 $L = 2(b + d)$	$I_X = \frac{d^2}{6}(3b + d)$ $I_X = \frac{d^2}{6}(b + 3d)$ $J_W = \frac{(b + d)^3}{6}$	$S_X = \frac{d}{3}(3b + d)$ $S_Y = \frac{b}{3}(b + 3d)$ $C = \frac{(b^2 + d^2)^{1/2}}{2}$	
 $L = b + 2d$	$I_X = \frac{d^3}{3}\left(\frac{2b + d}{b + 2d}\right)$ $I_Y = \frac{b^3}{12}$ $J_W = \frac{d^3}{3}\left(\frac{2b + d}{b + 2d}\right) + \frac{b^3}{12}$	$S_{XT} = \frac{d}{3}(2b + d)$ $S_Y = \frac{b^2}{6}$ $C_B = d\left(\frac{b + d}{b + 2d}\right)$ $C = \left[{C_T}^2 + \left(\frac{b}{2}\right)^2\right]^{1/2}$	$S_{XB} = \frac{d^2}{3}\left(\frac{2b + d}{b + d}\right)$ $C_T = \frac{d^2}{b + 2d}$
 $L = 2(b + d)$	$I_X = \frac{d^3}{6}\left(\frac{4b + d}{b + d}\right)$ $I_Y = \frac{b^3}{6}$ $J_W = \frac{d^3}{6}\left(\frac{4b + d}{b + d}\right) + \frac{b^2}{6}$	$S_{XT} = \frac{d}{3}(4b + d)$ $S_Y = \frac{b^2}{3}$ $C_B = \frac{d}{2}\left(\frac{2b + d}{b + d}\right)$ $C = \left[{C_T}^2 + \left(\frac{b}{2}\right)^2\right]^{1/2}$	$S_{XB} = \frac{d^2}{3}\left(\frac{4b + d}{2b + d}\right)$ $C_T = \frac{d^2}{2(b + d)}$
 $L = 2(b + d)$	$I_X = \frac{d^2}{6}(3b + d)$ $I_Y = \frac{b^3}{6}$ $J_W = \frac{d^2}{6}(3b + d) + \frac{b^3}{6}$	$S_X = \frac{d}{3}(3b + d)$ $S_Y = \frac{b^2}{3}$ $C = \frac{(b^2 + d^2)^{1/2}}{2}$	

(Continued)

Table 5.14 (Continued)
Properties of Welded Construction Treated as a Line

 $L = 2\,(2b + d)$	$I_X = \frac{d^2}{6}(6b+d)$ $I_Y = \frac{b^3}{3}$ $J = \frac{d^2}{6}(6b+d) + \frac{b^3}{3}$	$S_X = \frac{d}{3}(6b+d)$ $S_Y = \frac{2}{3}b^2$ $C = \frac{(b^2+d^2)^{1/2}}{2}$	
 $L = 2\,\pi r$	$I = \pi\, r^3$	$S_W = \pi\, r^2$	$J_W = 2\pi\, r^3$

Key:

π = 3.1416
b = Length of the horizontal weld, in. (mm)
C = Distance from the center of gravity to the point of combined stress, in. (mm)
C_B = Distance from the X-axis to the top, in. (mm)
C_T = Distance from the X-axis to the bottom, in. (mm)
C_{YR} = Distance from the Y-axis to far right side, in. (mm)
C_{YL} = Distance from the Y-axis to the far left side, in. (mm)
d = Length of the vertical weld, in. (mm)
J = Polar moment of inertia of an area, in.^{4} (mm^4)
J_w = Polar moment of inertia of a line weld, in.^{4}/in. (mm^4/mm), in.^{4} (mm^4)
L = Total length of the weld, in. (mm)
I = Moment of inertia, in.^{4} (mm^4)
I_X = Moment of inertia about the X-axis, in.^{4} (mm^4)
I_Y = Moment of inertia about the Y-axis, in.^{4} (mm^4)
r = Radius, in. (mm)
S = Section modulus of an area, in.^{3} (mm^3)
S_w = Section modulus of a line weld, in.^{3} (mm^3)
S_X = Section modulus about the X-axis
S_{XB} = Section modulus of the bottom piece about the X-axis
S_{XT} = Section modulus of the top piece about the X-axis
S_Y = Section modulus about the Y-axis
S_{YL} = Section modulus of the left piece about the Y-axis
S_{YR} = Section modulus of the right piece about the Y-axis

Source: Adapted from Blodgett, O. W., 1966, *Design of Welded Structures*, Cleveland: The James F. Lincoln Arc Welding Foundation, Section 7.4, Table 5.

In Step 4, the design shear strength on the effective area of weld metal having an ultimate tensile strength of 60,000 psi (413 MPa) is determined using LRFD procedures, as follows (see Table 5.8):

$$\phi F_n = 0.75\,(0.6\,F_{EXX})$$
$$= 0.75\,(0.6 \times 60\,000)$$
$$= 27{,}000 \text{ psi (186 MPa)} \tag{5.18}$$

where

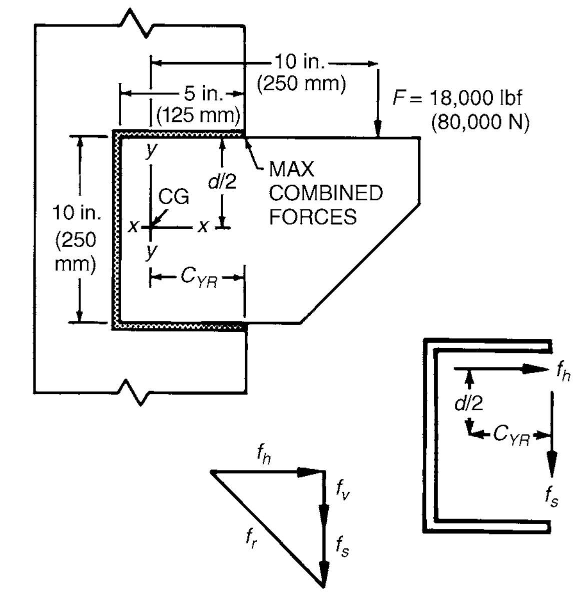
ϕ = LRFD resistance factor;
F_n = Nominal strength, kips (kN); and
F_{EXX} = Minimum specified tensile strength of the weld metal, ksi (MPa).

The effective throat is then determined, as follows:

$$E = \frac{f_t}{\phi F_n} = \frac{3540}{27{,}000} = 0.128 \text{ in. (3 mm)} \tag{5.19}$$

where

E = Effective throat, in. (mm);
f_t = Resultant force, lb (N);
ϕ = LRFD resistance factor; and
F_n = Nominal strength, kips (kN).



Key:

- CG = Center of gravity
- F = Applied load, lbf (N)
- C_{YR} = Greatest distance from CG in the horizontal direction, in. (mm)
- d = Length of the vertical weld, in. (mm)
- f_h = Horizontal force component, lbf (N);
- f_r = Resultant force, lb (N)
- f_s = Force component due to shear, lbf (N)
- f_v = Vertical twisting force component, lbf (N)

Source: Adapted from Blodgett, O. W., 1966, *Design of Welded Structures*, Cleveland: The James F. Lincoln Arc Welding Foundation, Figure 15.

Figure 5.40—Bracket Joined to a Column Face with a Fillet Weld

Assuming an equal leg fillet weld size, the minimum leg size is equal to the following:

$$S = \frac{E}{0.707} = \frac{0.128}{0.707} = 0.181 \text{ in. (5 mm)} \qquad (5.20)$$

where

S = Leg size, in. (mm); and
E = Effective throat, in. (mm).

By using the method that involves treating the weld as a line, the appropriate weld size can be determined. In this example, a 3/16 in. (5 mm) fillet weld is adequate to transfer the applied load to the column flange. Thus, this weld size should be specified in the welding symbol.

TUBULAR CONNECTIONS

Tubular members, also called *hollow structural sections*, are used in structures such as drill rigs, space frames, trusses, booms, and earthmoving and mining equipment.[47] They have the advantage of minimizing deflection under load because of their greater rigidity when compared to standard structural shapes. Various types of welded tubular connections, the component designations, and nomenclature are shown in Figure 5.41.

With structural tubing, holes need not be cut at intersections. Therefore, the connections are characterized by high strength and stiffness. However, connections made with complete joint penetration groove welds must be given special consideration, and appropriate care must be taken to ensure weld quality and that adequate fusion exists at the root. A complete joint penetration weld must be made from one side only and without backing as the small tube size and configuration prevent access to the root side of the weld. Special skill is required to make tubular connections using complete joint penetration groove welds from one side.

With relatively small thin-walled tubes, the end of the brace tube may be partially or fully flattened. The end of the flattened section is trimmed at the appropriate angle to abut against the main member where it is to be welded. This design should only be used with relatively low-load conditions because the load is concentrated on a narrow area of the main tube member. The flattened section of the brace member must be free of cracks.

WELD JOINT DESIGN

When tubular members are fit together for welding, the end of the branch member or brace is normally contoured to the shape of the main member. In the case of T-connections [see Figure 5.41(C)], the members may be joined with their axes at 80° to 100°. For Y- and K-connections [see Figure 5.41(D) and 5.41(E)], an angle less than 80° would be used. The tubes may have a circular or rectangular shape. In addition, the branch member may be equal in size or smaller than the main member.

The angle between the adjacent outside tube surfaces in a plane perpendicular to the joint (the local dihedral angle, Ψ), can vary around the joint from about 150° to 30°. To accommodate this, the weld joint design and welding procedures used must vary around the joint to obtain a weld with an adequate throat dimension.

47. The welding of steel tubular structures is covered in American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel*, AWS D1.1, Miami: American Welding Society.

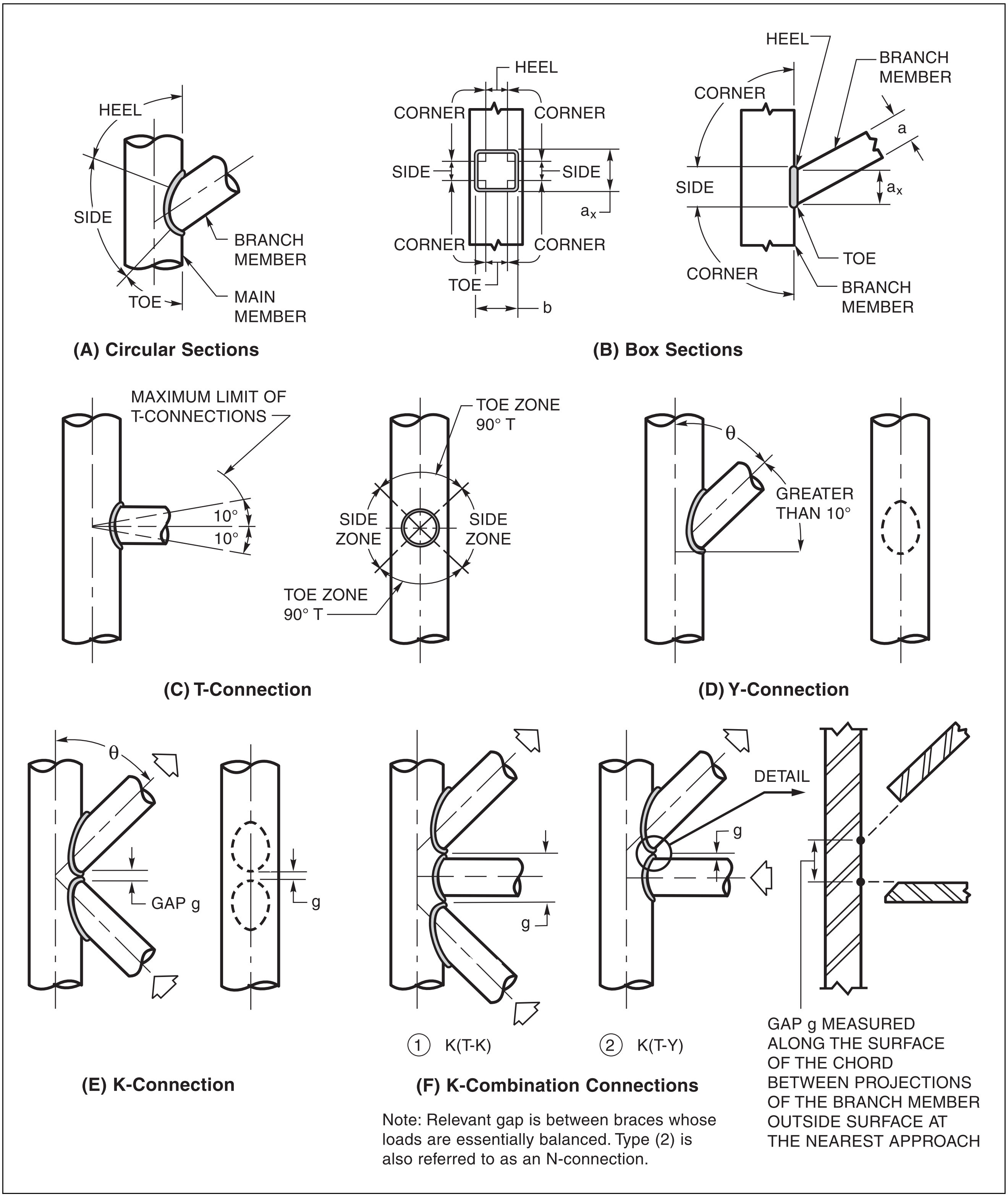


Figure 5.41—Welded Tubular Connections, Components, and Nomenclature

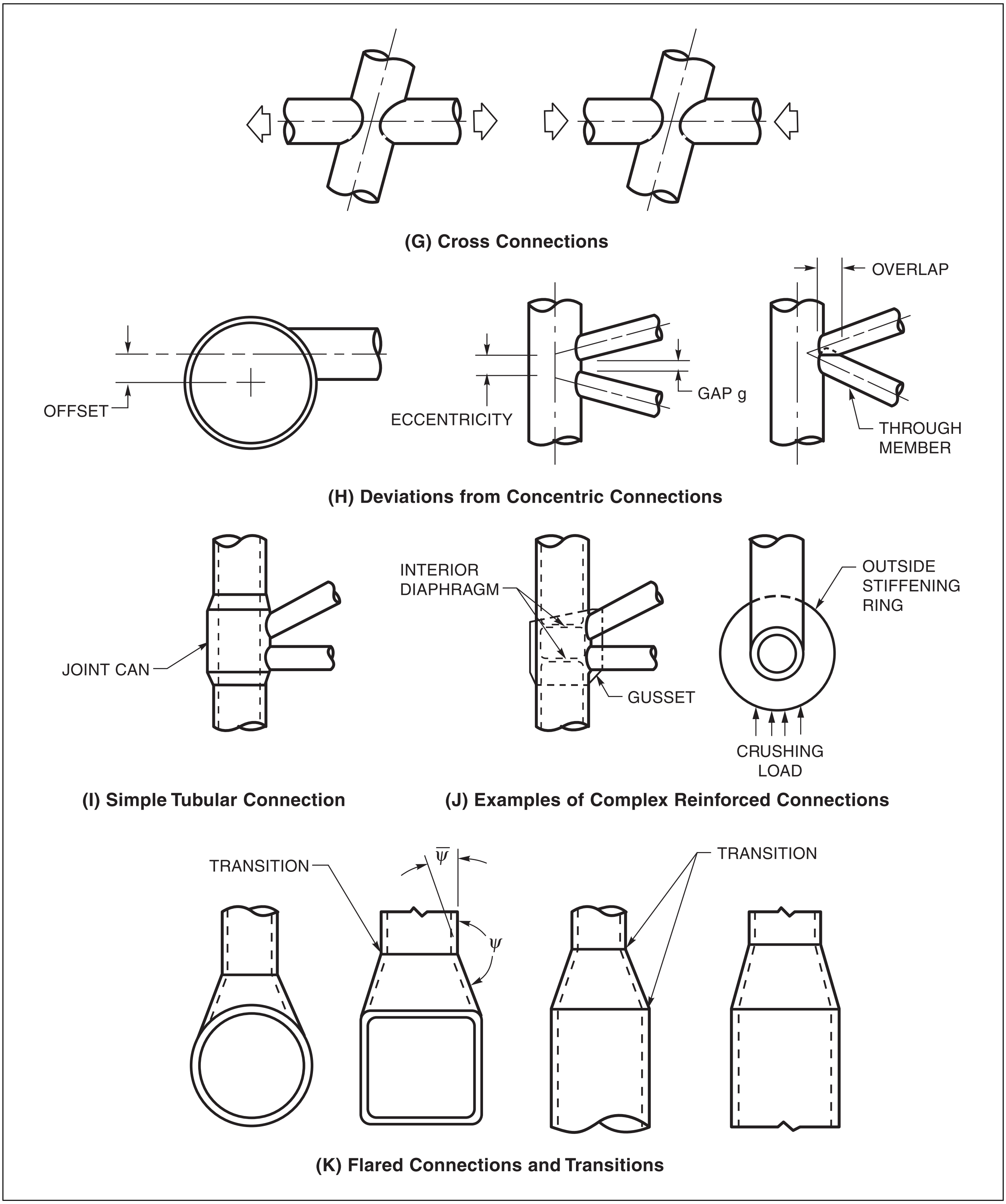
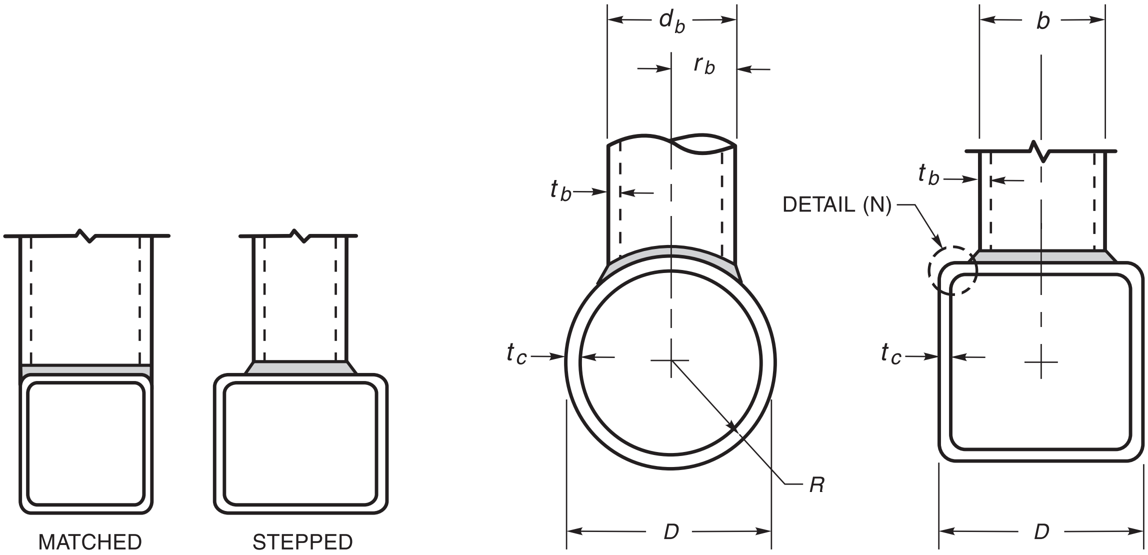
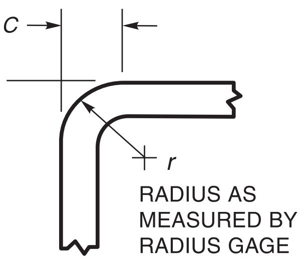


Figure 5.41 (Continued)—Welded Tubular Connections, Components, and Nomenclature



(L) Connection Types for Box Sections

(M) Geometric Parameters



(N) Corner Dimension or Radius Measurement

PARAMETER	CIRCULAR SECTIONS	BOX SECTIONS
β	r_b/R OR d_b/D	b/D
η	—	a_x/D
γ	R/t_c	$D/2t_c$
τ	t_b/t_c	t_b/t_c
θ	ANGLE BETWEEN MEMBER CENTERLINES	
Ψ	LOCAL DIHEDRAL ANGLE AT A GIVEN POINT ON WELDED JOINT	
C	CORNER DIMENSION AS MEASURED TO THE POINT OF TANGENCY OR CONTACT WITH A 90° SQUARE PLACED ON THE CORNER	

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Figure 2.14.

Figure 5.41 (Continued)—Welded Tubular Connections, Components, and Nomenclature

Tubular joints are normally accessible for welding only from outside the tubes. Therefore, the joints are generally made with single groove or fillet welds. Groove welds may be designed for complete or partial joint penetration, depending upon the load conditions. To obtain adequate joint penetration, shielded metal arc, gas metal arc, and flux cored arc welding are generally used to make tubular joints in structures.

Suggested groove designs[48] for complete joint penetration with four dihedral angle ranges are presented in Figure 5.42. The areas of the circular and box connections to which the groove designs of Figure 5.42 apply are shown in Figure 5.43(A), 5.43(B), and 5.43(C), respectively. In Figure 5.42, the specified root opening, *R*, or the width of a backing weld, *W*, depends upon the welding process and the groove angle. The backing welds, which are not considered part of the throat of the joint design, provide a sound root condition for the deposition of the production weld.

Suggested groove designs for partial joint penetration groove welds for circular and box connections are shown in Figure 5.44. The sections of circular and box connections to which they apply are shown in Figure 5.45.

With more conventional prequalified partial joint penetration welds, the variation of the dihedral angles (Ψ) around the joint, the inaccessibility for welding from the inside, and the differences in penetration of the various processes motivate a separate consideration of the questionable root area of the weld as contrasted to direct tabulation of the effective throat. An allowance should be made for incomplete fusion at the throat of partial joint penetration groove welds. This allowance, which is termed the loss factor, assures that the actual throat of the weld is not smaller than that specified by the design requirement. The loss factor, Z, is shown in Table 5.15 for various local dihedral angles and welding processes.

Suggested fillet weld details for T-, K-, and Y-connections in circular tubes are shown in Figure 5.46. These are limited to $\beta \leq 0.33$ for circular sections and $\beta \leq 0.8$ for box sections.[49] The recommended allowable stress on the effective throat of partial joint penetration groove welds and fillet welds in steel T-, K-, and Y-connections is 30% of the tensile strength of the classification of the weld metal. For example, an E7018 electrode has the tensile strength of 70,000 psi (480 MPa). The stress on the adjoining base metal should not exceed that permitted by the applicable code.

48. These groove designs meet the joint geometry requirements for prequalified welding procedures in American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.

49. Parameter β is defined in Figure 5.41.

A welded tubular connection is limited in strength by four factors. These are:

1. Local or punching shear failure,
2. Uneven distribution of the load on the welded connection,
3. General collapse, and
4. Lamellar tearing.

These limitations are discussed below.

LOCAL FAILURE

When a circular or stepped T-, K-, or Y-connection (see Figure 5.46) is made by simply welding the branch member to the main member, the local stresses at a potential failure surface through the main member wall may limit the useable strength of the main member. The actual localized stress situation is more complex than simple shear. The term *punching shear* describes a local failure condition in which the main member fails adjacent to the weld by shear.

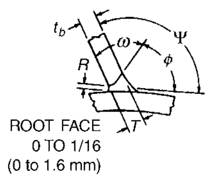
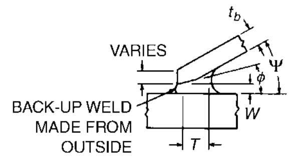
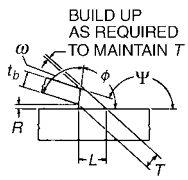
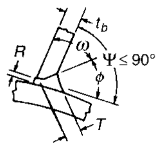
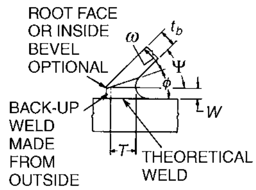
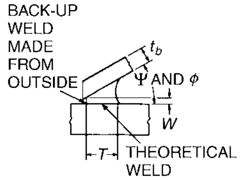
Whichever the mode of failure of the main member, the allowable punching shear stress is a conservative representation of the average shear stress at failure in static tests of simple welded tubular connections. The method used to determine the punching shear stress in the main member is presented in *Structural Welding Code—Steel*, AWS D1.1.[50] The actual punching shear in the main member caused by the axial force and any bending moment in the branch member must be determined and compared with the allowable punching shear stress. The effective area and length of the weld, as well as its section modulus, must be determined to treat the axial force and bending moment on the joint. These joint properties are factored into the stress and force calculations, as described in *Structural Welding Code—Steel*, AWS D1.1.[51]

UNEVEN DISTRIBUTION OF LOAD

Another condition that can limit the strength of a welded connection is the uneven distribution of a load on a weld. Under load, some bending of the main member could take place, which might cause an uneven distribution of the force applied to the weld. As a result, some yielding and redistribution of stresses may have to take place for the connection to reach its design load. To provide for this, welds at their ultimate breaking strength in T-, K-, and Y-connections [See Figure 5.41(C), (D), and (E)] must be capable of developing the lesser of (1) the yield strength of the branch member

50. See Reference 32.

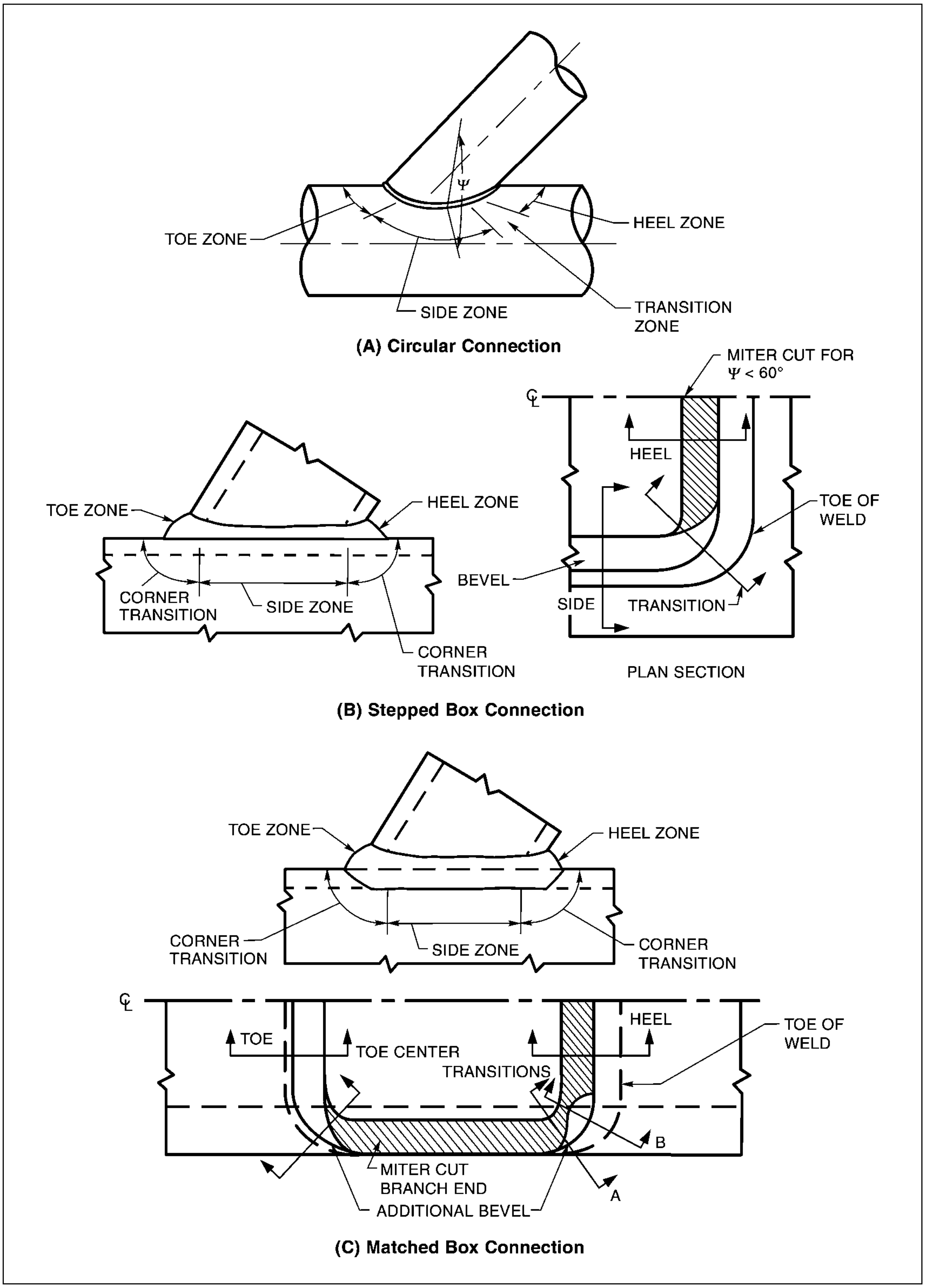
51. See Reference 32.

								
						Transition from Ⓒ to Ⓓ		
								
		Ⓐ (3) Ψ = 180°–135°		Ⓑ (3) Ψ = 150°–50°		Ⓒ (3) Ψ = 75°–30°		Ⓓ (3) Ψ = 37-1/2°–15°
End preparation (ω)	max	90°		90°		(a)		
	min	45°		10° or 45° for Ψ > 105°		10°		
Fitup or root opening (R)		FCAW SMAW (1)	GMAW FCAW (2)	FCAW SMAW (1)	GMAW FCAW (2)		W max. (b)	ϕ
	max	3/16 in. (5 mm)	3/16 in. (5 mm)	1/4 in. (6 mm)	1/4 in. (6 mm) for ϕ > 45° 5/16 in. (8 mm) for $\phi \leq$ 45°	FCAW SMAW (1)	1/8 in. (3 mm) 3/16 in. (5 mm)	22-1/2°–37-1/2° 15°–20-1/2°
	min	1/16 in. (1.6 mm) No min for ϕ > 90°	1/16 in. (1.6 mm) No min for ϕ > 120°	1/16 in. (1.6 mm)	1/16 in. (1.6 mm)	GMAW FCAW (2)	1/8 in. (3 mm) 1/4 in. (6 mm) 3/8 in. (10 mm) 1/2 in. (13 mm)	30°–37-1/2° 25°–30° 20°–25° 15°–20°
Joint included angle ϕ	max			60° for $\Psi \leq$ 105°		37-1/2° if more use Ⓑ		
	min			37-1/2° if less use Ⓒ		1/2 Ψ		
Completed weld	T	$\geq t_b$		$\geq t$ for Ψ > 90° $\geq t/\sin \Psi$ for $\Psi \leq$ 90°		$\geq t/\sin \Psi$ but need not exceed 1.75t Weld may be built up to meet this		$\geq 2t_b$
	L	$\geq t/\sin \Psi$ but need not exceed 1.75t						

(a) Otherwise as needed to obtain required ϕ.
(b) Initial passes of back-up weld are discounted until width of groove (W) is sufficient to assure sound welding; the necessary width of weld groove (W) is provided by back-up weld.

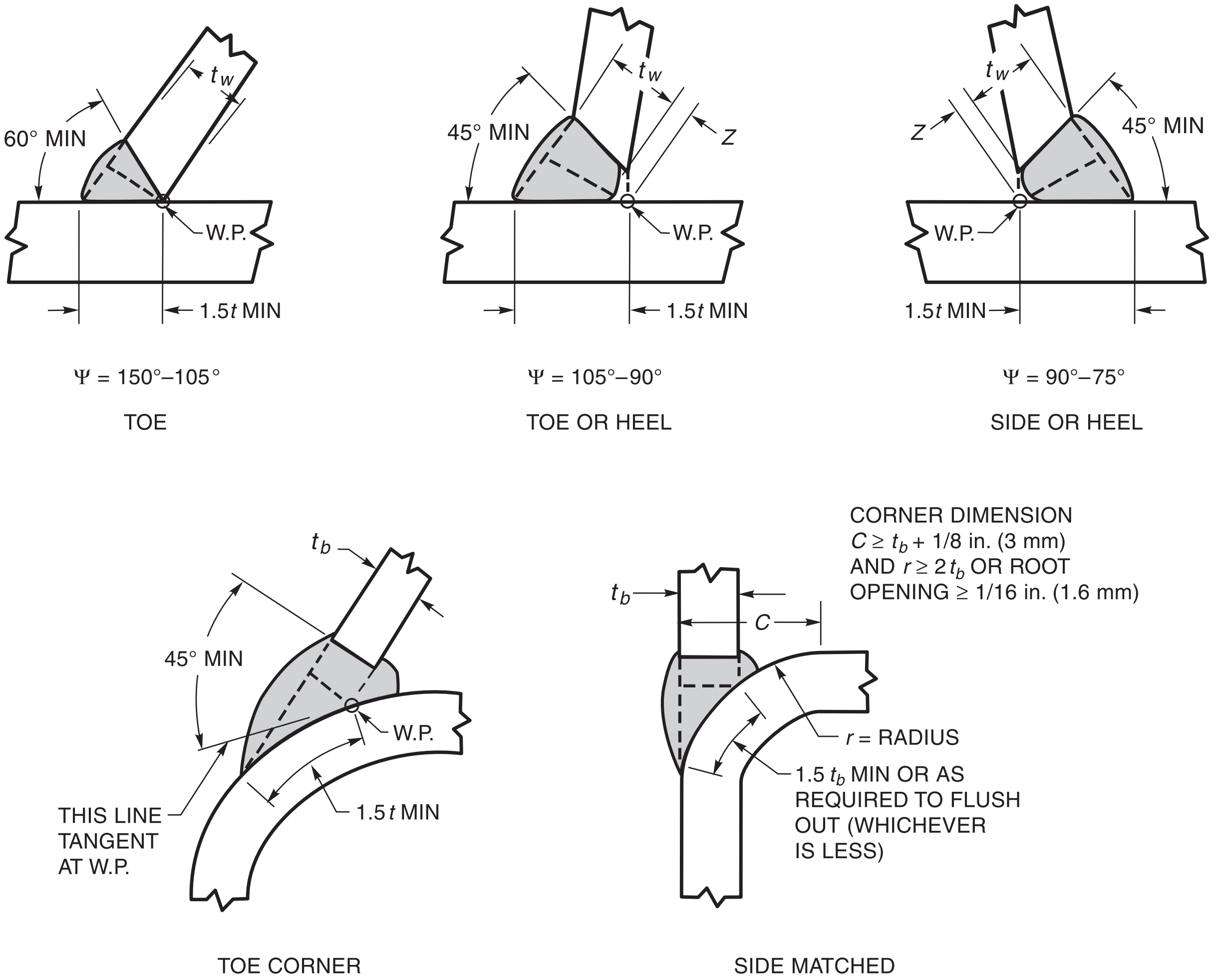
Notes:
1. These root details apply to SMAW and FCAW (self-shielded).
2. These root details apply to GMAW (short-circuiting transfer and FCAW [gas shielded]).
3. See Figure 5.43 for locations on the tubular connection.

Figure 5.42—Joint Designs for Complete Joint Penetration in Simple T-, K-, and Y-Tubular Connections



Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, D1.1:2000, Miami: American Welding Society, Figure 3.5.

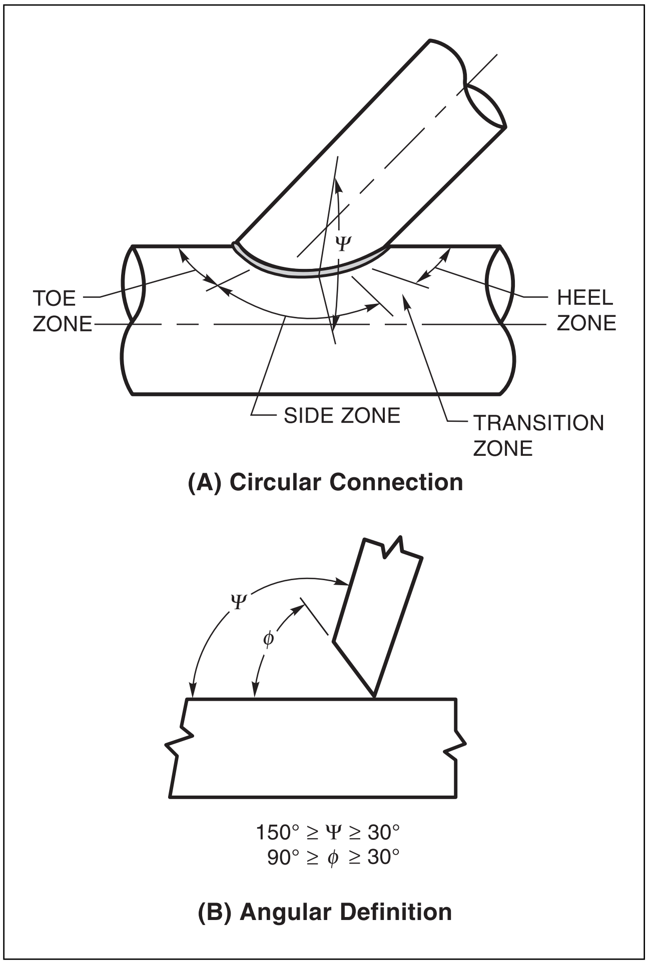
Figure 5.43—Locations of Complete Joint Penetration Groove Weld Designs on Tubular Connections: (A) Circular Sections; (B) Box Sections; and (C) Matched Box Connections



Notes:
1. t = Thickness of the thinner section, in. (mm).
2. Bevel to feather edge except in transition and heel zones.
3. Root opening: 0 in. to 3/16 in. (0 mm to 5 mm).
4. Not prequalified for under 30°.
5. Weld size (effective throat) $t_w \geq t$; see Table 5.14 for the loss factor, Z.
6. Calculations per AWS D1.1:2000, Section 2.40.1.3, shall be done for leg length less than 1.5t, as shown.
7. For box sections, joint preparation for corner transitions shall provide a smooth transition from one detail to another. Welding shall be carried continuously around corners, with corners fully built up and all weld starts and stops within flat faces.
8. The local dihedral angle, Ψ, is defined as the angle, measured in a plane perpendicular to the line of the weld, between tangents to the outside surfaces of the tubes being joined at the weld.
9. W.P. = Work point.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, D1.1:2000, Miami: American Welding Society, Figure 3.5.

Figure 5.44—Joint Designs for Partial Joint Penetration Groove Welds in Simple T-, K- and Y-Tubular Connections



Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, D1.1:2000, Miami: American Welding Society, Figure 3.5.

Figure 5.45—Location of Partial Joint Penetration Groove Weld Designs in Tubular Connections: (A) Circular Connection and (B) Angular Definition

or (2) the ultimate punching shear strength of the shear area of the main member. These conditions are illustrated in Figure 5.47. This particular part of the design is best handled by working in terms of unit force (lb/linear in. [N/linear mm]).

As shown in Figure 5.47(A), the ultimate breaking strength of fillet welds and partial joint penetration groove welds is computed at 2.67 times the basic allowable stress for 60 ksi (413 MPa) and 70 ksi (480 MPa) tensile strength weld metal, and at 2.2 times for higher strength weld metals.

The unit force on the weld from the branch member at its yield strength, Figure 5.47(B), is as follows:

$$f_1 = \sigma_y t_b \tag{5.21}$$

where

f_1 = Unit force, lb/in. (N/mm);
σ_y = Yield strength of branch member, psi (MPa); and
t_b = Thickness of branch member, in. (mm).

The ultimate shear force on the main-member shear area at failure, shown in Figure 5.47(C), is as follows:

$$f_2 = 1.8\tau_a t \tag{5.22}$$

where

f_2 = Ultimate unit shear normal to the weld, lb/in. (N/mm);
τ_a = Allowable shear stress, psi (MPa); and
t = Thickness of the main member, in. (mm).

The unit shear force per inch (mm) on the weld is as follows:

$$f_3 = \frac{f_2}{\sin\theta} = \frac{1.8\tau_a t}{\sin\theta} \tag{5.23}$$

where

f_3 = Unit shear force per inch (mm);
f_2 = Ultimate unit shear normal to the weld, lb/in. (N/mm);
θ = Angle between the two members, degrees (radians);
τ_a = Allowable shear stress, psi (MPa); and
t = Thickness of the main member, in. (mm).

GENERAL COLLAPSE

As previously noted, the strength of the connection also depends on what is termed *general collapse*. The strength and stability of the main member in a tubular connection should be investigated using the proper technology and in accordance with the applicable design code. General collapse should not be a limiting factor if (1) the main member has sufficient thickness to resist punching shear and (2) this thickness extends beyond the branch members for a distance of at least one-fourth of the diameter of the main member.

Table 5.15
Loss Factors for Incomplete Fusion at the Root of Partial Joint Penetration Groove Welds

Groove Angle, ϕ	Welding Process* (V or OH)†	Loss Factor, Z‡ in.	Loss Factor, Z‡ mm	Welding Process* (H or F)†	Loss Factor, Z‡ in.	Loss Factor, Z‡ mm
$\phi \geq 60°$	SMAW	0	0	SMAW	0	0
	FCAW-S	0	0	FCAW-S	0	0
	FCAW-G	0	0	FCAW-G	0	0
	GMAW	N/A§	N/A	GMAW	0	0
	GMAW-S	0	0	GMAW-S	0	0
$60° > \phi \geq 45°$	SMAW	1/8	3	SMAW	1/8	3
	FCAW-S	1/8	3	FCAW-S	0	0
	FCAW-G	1/8	3	FCAW-G	0	0
	GMAW	N/A	N/A	GMAW	0	0
	GMAW-S	1/8	3	GMAW-S	1/8	3
$45° > \phi \geq 30°$	SMAW	1/4	6	SMAW	1/4	6
	FCAW-S	1/4	6	FCAW-S	1/8	3
	FCAW-G	3/8	10	FCAW-G	1/4	6
	GMAW	N/A	N/A	GMAW	1/4	6
	GMAW-S	3/8	10	GMAW-S	1/4	6

* FCAW-S = Self-shielded flux cored arc welding; GMAW = Spray or globular transfer gas metal arc welding; FCAW-G = Gas shielded flux cored arc welding; GMAW-S = Short circuiting transfer gas metal arc welding.
† V = Vertical position; OH = Overhead position; H = Horizontal position; F = Flat position.
‡ Refer to Figure 5.46.
§ N/A = Not applicable.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, D1.1:2000, Miami: American Welding Society, Table 2.8.

THROUGH-THICKNESS FAILURES

In tubular connections such as those shown in Figures 5.41 through 5.47, the force must be transmitted through the thickness of the main member when the axial force on the branch member is tension. The ductility and notch toughness of rolled metals is significantly lower in the through-thickness (short-transverse) direction than in the longitudinal or transverse directions. Thus, a tubular member could delaminate because of tensile stresses transmitted through the thickness.

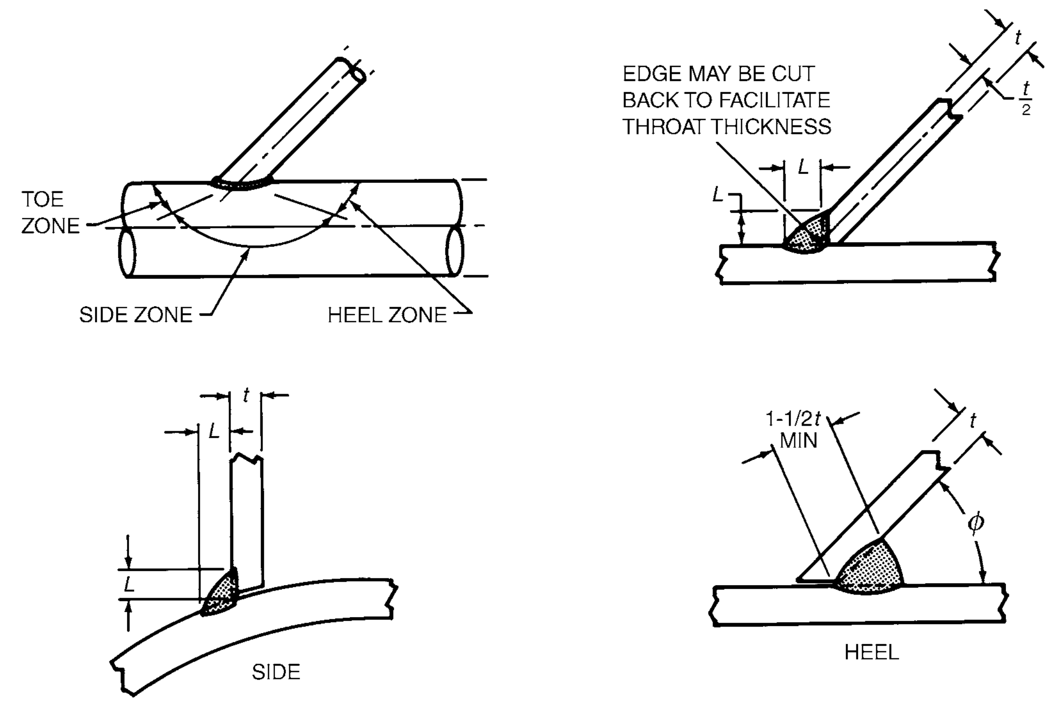
To avoid this condition, an interior diaphragm or continuity plates in combination with gusset plates or stiffening rings, as shown in Figure 5.41(J), can be employed at highly stressed connections. To reduce the through-thickness tensile stresses further, the diaphragm plate can penetrate the shell of the main member as shown in Figure 5.41(J) (left). These continuity plates are also used to prevent the main member from buckling.

The resulting single-bevel-groove weld, in which the main member is grooved, transfers the delaminating forces from the primary structural member to the secondary structural member. This follows the principles suggested earlier in the chapter regarding the beveling of the through-thickness member to avoid lamellar tears from weld shrinkage.

FATIGUE

The design of welded tubular structures subject to cyclic loading is handled in the same manner as discussed previously. The specific treatment may vary with the applicable code for the structure.[52] Stress categories

52. Such codes include American Welding Society (AWS) Committee on Structural Welding *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society; and American Petroleum Institute (API), *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms,* API RP 2A, 11th ed., Dallas: American Petroleum Institute.



Notes:
1. t = Thickness of the thinner part, in. (mm)
2. $L \leq t$
3. Root opening = 0 in. to 3/16 in. (0 mm to 5 mm)
4. ϕ = 15° min
5. $\beta \leq 0.33$ for circular sections and 0.8 for box sections

Figure 5.46—Fillet Weld Details for T-, K-, and Y-Connections

are assigned to various types of tube(s), attachments to tube(s), joint designs, and loading conditions. The total cyclic fatigue stress range for the desired service life of a particular situation can be determined.

Fatigue behavior can be improved by taking one or more of the following actions:

1. Adding a capping layer to provide a smooth contour with the base metal,
2. Grinding the weld face transverse to the weld axis, and
3. Peening the toe of the weld with a blunt instrument to cause local plastic deformation and to smooth the transition between the weld and base metals.

ALUMINUM STRUCTURES

The concepts and methods employed to design structures in aluminum are generally the same as those used with steel or other metals.[53] The methods and stress values recommended for structural aluminum design are set forth in the Aluminum Association's *Aluminum*

53. Welding requirements applicable to welded aluminum structures are provided in American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Aluminum,* ANSI/AWS D1.2, Miami: American Welding Society.

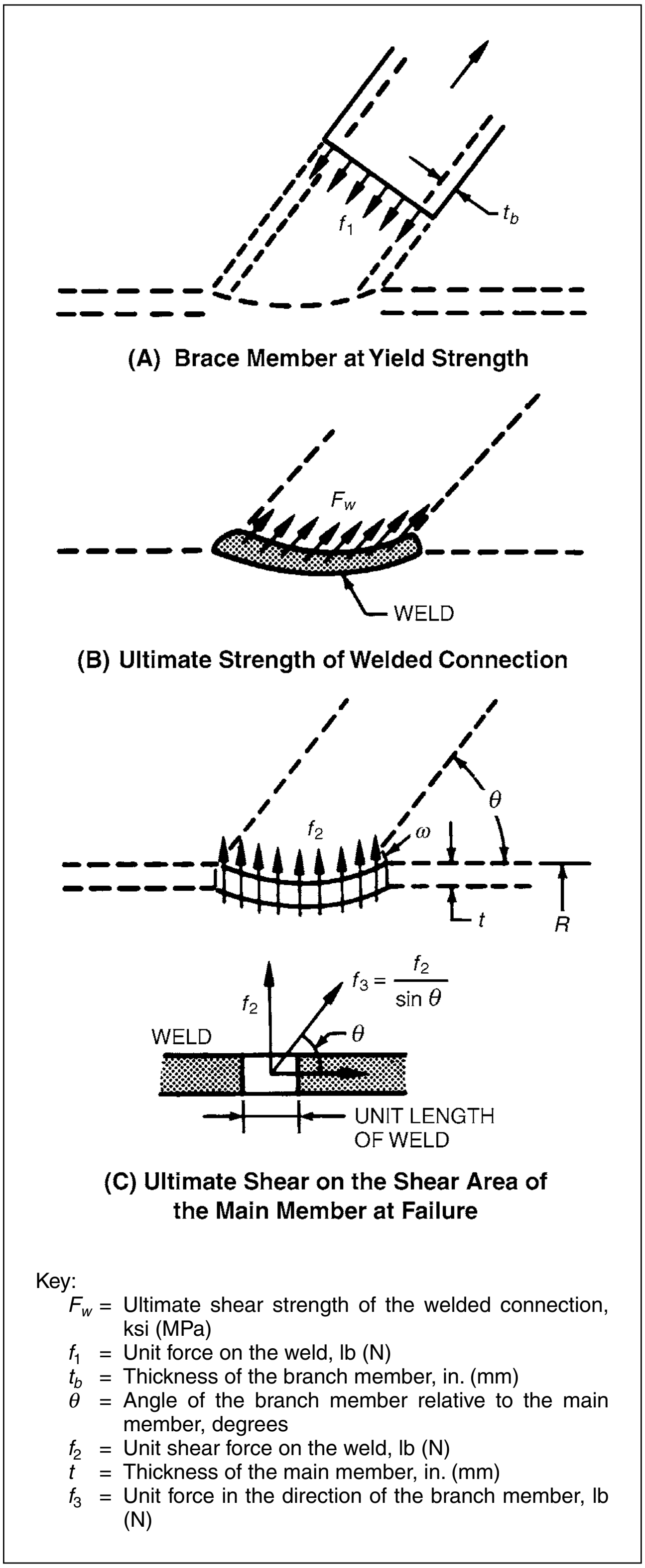


Figure 5.47—Loads on Welded Tubular Connections

Design Manual: Specifications and Guidelines for Aluminum Structures.[54]

Cast and wrought aluminum products are available in many structural forms and shapes. The designer can take advantage of the light weight of aluminum by utilizing available aluminum structural forms. Proper engineering design minimizes the number of joints and amount of welding without affecting product requirements. This, in turn, results in a good appearance and the proper functioning of the product by limiting distortion caused by heating. To eliminate joints, the designer may use castings, extrusions, forgings, or bent or roll-formed shapes to replace complex assemblies. Special extrusions that incorporate edge preparations for welding may provide savings in manufacturing costs. Typical designs are shown in Figure 5.48. An integral lip can be provided on the extrusion to facilitate alignment and serve as a weld backing.

For cost-effective fabrication, designers should employ the least expensive metal-forming and metal-working processes, minimize the amount of welding required, and place welds at locations of low stress. A simple example is the fabrication of an aluminum tray, as shown in Figure 5.49. Instead of using five pieces of sheet and eight welds located at the corners, as illustrated in Figure 5.49(A), this unit could be fabricated from three pieces of sheet, one of which is formed into the bottom and two sides, as shown in 5.49(B), thereby reducing the amount of welding.

Further reduction in welding could be achieved by additional forming, as depicted in Figure 5.49(C). This forming also improves performance as butt or lap joints can be welded instead of corners. However, some distortion would likely take place in the two welded sides because all the welds are located in these two planes. The refinement of a design to limit only the amount of welding could lead to problems in fabrication, end use, or appearance. Therefore, the extent of welding should not be the single consideration in weldment design.

WELD JOINTS

Butt, lap, edge, corner, and T-joints may be used in aluminum design. For structural applications, edge and corner joints should be avoided because they are harder to fit, weaker, and more prone to fatigue failure than other joints. These two joints are commonly used in sheet metal fabrication, however.

54. Aluminum Association, *Aluminum Design Manual: Specifications and Guidelines for Aluminum Structures*. Washington, D.C.: Aluminum Association.

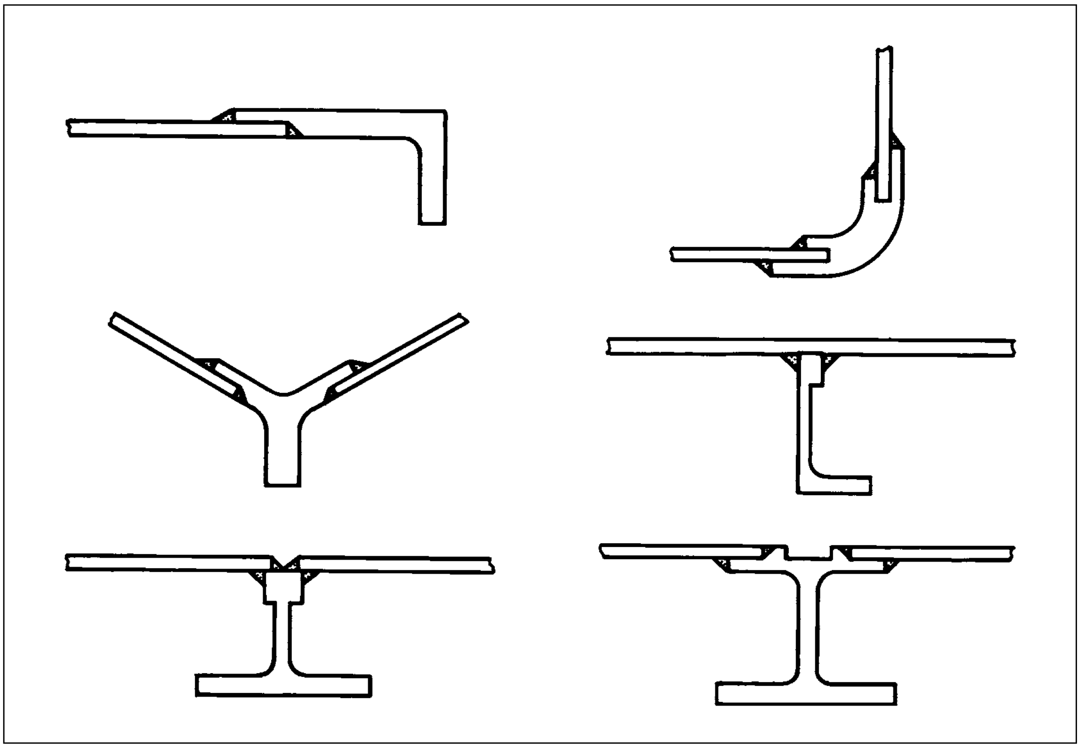


Figure 5.48—Typical Extrusion Designs Incorporating Desired Joint Geometry, Alignment, and Reinforcement Between Different Thicknesses

Butt Joints

Butt joints are characterized by simplicity of design, good appearance, and better performance under cyclic loading than other types of joints. However, these joints require accurate alignment and joint edge preparation on thicknesses above 1/4 in. (6 mm) to permit satisfactory root penetration. In addition, backgouging and a backing weld are recommended to ensure complete fusion on thicker sections.

Sections of different thicknesses may be butted together and welded. However, it is better to bevel the thicker section before welding to reduce the concentration of stress, particularly when the joint will be exposed to cyclic loading in service.

When thin aluminum sheets are to be welded to thicker sections, it is difficult to obtain adequate depth of fusion in the thicker section without melting away the thin section. This difficulty can be avoided by extruding or machining a lip on the thicker section equal in thickness to that of the thin part, as shown in Figure 5.50(B). This design will also provide a better heat balance and further reduce the heat-related distortion. If the thicker section is an extrusion, a welding lip can be incorporated in the design as described previously.

Lap Joints

Lap joints are used more frequently with aluminum alloys than with most other metals. In thicknesses up to 1/2 in. (13 mm), it may be more economical to use single-lap joints with fillet welds on both sides rather than butt joints welded with complete joint penetration. Lap joints require no edge preparation, are easy to fit, and require less fixturing than butt joints. The efficiency of lap joints ranges from 70% to 100%, depending on the composition and temper of the base metal. Preferred types of lap joints are presented in Figure 5.51.

Lap joints create an offset in the plane of the structure unless the members are in the same plane and strips are used on both sides of the joint. Those with an offset tend to rotate under load. Moreover, lap joints may be impractical if the joint is not accessible for welding on both sides.

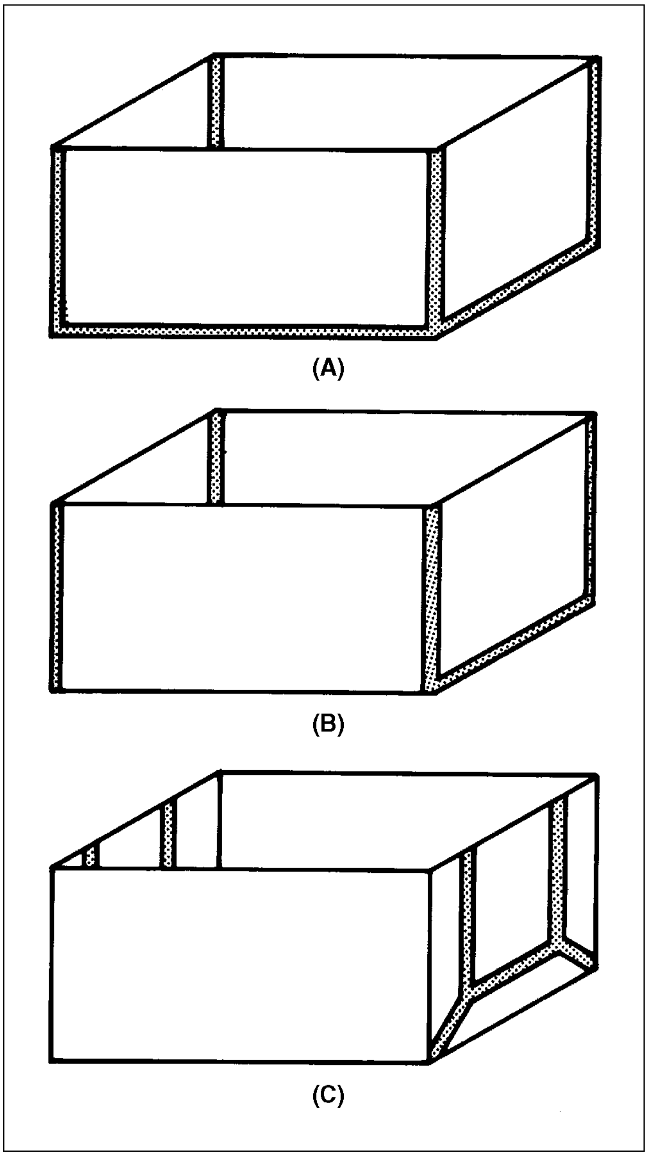


Figure 5.49—Designs for an Aluminum Tray

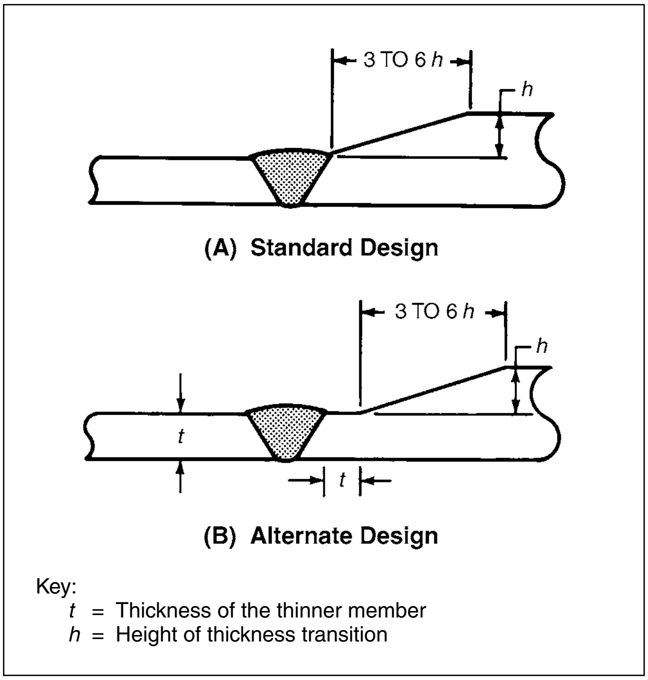


Figure 5.50—Recommended Transition Joints

T-Joints

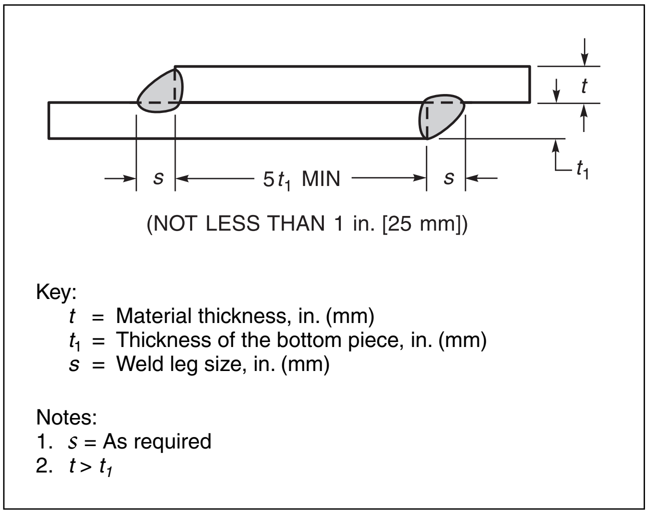
T-joints seldom require edge preparation because they are usually connected by fillet welds. The welds should have complete fusion to or beyond the root (corner) of the joint. A single- or double-bevel-groove weld in combination with fillet welds may be used with thicknesses above 3/4 in. (19 mm) to reduce the amount of weld metal. T-joints are generally easily fitted and normally require no backgouging. Necessary fixturing is usually quite simple.

A single fillet weld is not recommended for use in a T-joint. Although the joint may have adequate shear and tensile strength, it is very weak when loaded with the root of the fillet weld in tension. Small continuous fillet welds should be used on both sides of the joint rather than large intermittent fillet welds on both sides or a large continuous fillet weld on one side. Continuous fillet welding is recommended to improve fatigue life and prevent crevice corrosion and crater cracks. The suggested allowable shear stresses in fillet welds for building and bridge structures are presented in the *Aluminum Design Manual*: *Specifications and Guidelines for Aluminum Structure*.[55]

JOINT DESIGN

In general, the designs for joints welded in aluminum are similar to those for steel joints.[56] However, alumi-

55. See Reference 54.
56. Suggested weld joint designs are presented in Oates, W. R., and A, M. Saitta, eds, 1998, *Materials and Applications—Part 2*, Vol. 4 of the *Welding Handbook*, 8th ed., Miami: American Welding Society; American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Aluminum,* ANSI/AWS D1.2, Miami, American Welding Society; and Sharp, M. L., G. E. Nordmark, and C. C. Menzemer, 1996, *Fatigue Design of Aluminum Components and Structures*, New York: McGraw Hill.



Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 2.5.

Figure 5.51—Preferred Types of Lap Joints

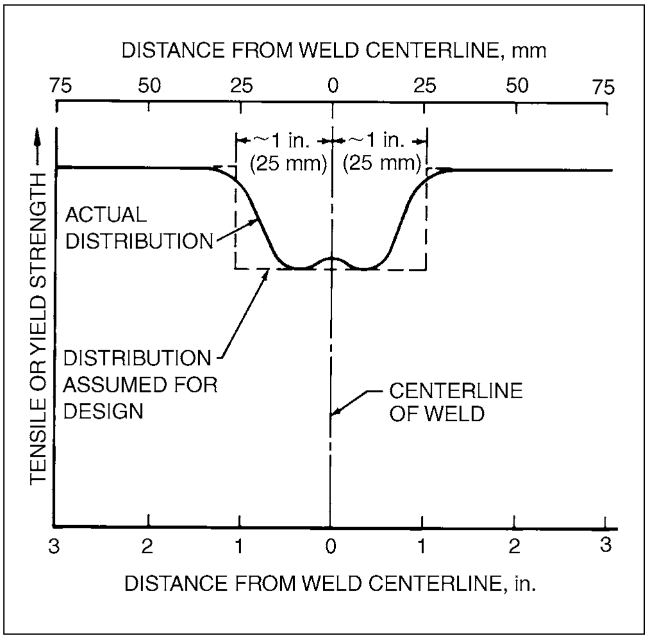


Figure 5.52—Distribution of Tensile or Yield Strength Across a Weld in Aluminum Member to Reduce Stress Concentration at the End of a Connection

num joints normally have smaller root openings and larger groove angles. To provide adequate shielding of the molten aluminum weld metal, larger gas nozzles are usually employed on welding guns and torches. The excellent machinability of aluminum makes J- and U-groove preparations economical due to a reduction in the volume of weld metal used, especially on thick sections.

EFFECTS OF WELDING ON STRENGTH

Aluminum alloys are normally used in the strain-hardened or heat-treated conditions, or a combination of both, to take advantage of their high strength-to-weight ratios. The effects of strain hardening or heat treatment are wholly or partially negated when aluminum is exposed to the elevated temperatures encountered in welding. The heat of welding softens the base metal in the heat-affected zone. The extent of softening is related to the section thickness, original temper, heat input, and the rate of cooling. The lower strength heat-affected zone must be considered in design. The orientation of the heat-affected zone with respect to the direction of stress and its proportion of the total cross section determines the allowable load on the joint.

The variation in tensile or yield strength across a welded joint in an aluminum structure is illustrated in Figure 5.52. With plate, the extent of decreased properties is considered to be a 2 in. (50 mm) wide band with the weld in the center. This band will be narrower when joining sheet gauges with an automatic welding process. The minimum mechanical properties for most commonly used welded aluminum alloys are given in the *Aluminum Design Manual*: *Specifications and Guidelines for Aluminum Structures*.[57] The minimum tensile properties for those alloys approved for work covered by *Structural Welding Code—Aluminum*, ANSI/AWS D1.2-97[58] are shown in Table 5.16.

Transverse welds in columns and beams should be located at points of lateral support to reinforce the weld and the heat-affected zone to prevent buckling. The weaker heat-affected zone effects of longitudinal welds in structural members can be neglected if the softened zone is less than 15% of the total cross-sectional area. Circumferential welds in piping or tubing may reduce bending strength; longitudinal welds usually have little effect on buckling strength when the heat-affected zone is a small percentage of the total area of the cross section.

57. See Reference 55.
58. American Welding Society (AWS) Committee on Structural Welding, 1997, *Structural Welding Code—Aluminum*. ANSI/AWS D1.2-97, Miami: American Welding Society.

Table 5.16
Strength of Welded Aluminum Alloys (GTAW or GMAW with No Postweld Heat Treatment)

Material Group No.	Alloy	Temper	Product	Thickness Range, in. (mm)	Minimum Tensile Strength, ksi (MPa)
21	1060	-O, -H12, -H14, -H16, -H18, -H22, -H24, -H26, -H28, -H112, -H113, -F	Sheet and plate	Up through 3.000 (75)	8 (55)
			Extrusions	All	8.5 (59)
21	1100	-O, -H12, -H14, -H16, -H18, -H22, -H24, -H26, -H28, -H112, -H113, -F	All	Up through 3.000 (75)	11 (75)
24	2219	-T62, -T81, -T851,	All	Up through 2.999 (75)	35 (240)
		-T8510, -T8511, -T87	Plate	3.000–6.000 (75–150)	35 (240)
		-T6, -T852	Forgings	3.000–4.000 (75–100)	35 (240)
21	3003	-O, -H12, -H14, -H16, -H18, -H22, -H24, -H26, -H28, -H112, -H113, -F	All	Up through 3.000 (75)	14 (95)
21	Alclad 3003	-O, -H12, -H14, -H16, -H18, -H112, -H113, -F, -H22, -H24, -H26	Tube	All	13 (90)
			Sheet and plate	Up through 0.499 (13)	13 (90)
			Plate	0.500–3.000 (13–75)	14 (95)
22	3004	-O, -H22, -H24, -H26, -H28, -H32, -H34, -H36, -H38, -H112, -F	All	Up through 3.000 (75)	22 (150)
22	Alclad 3004	-O, -H22, -H24, -H26, -H32, -H34, -H36, -H38, -H112, -F	Sheet and plate	Up through 0.499 (13)	21 (145)
			Plate	0.500–3.000 (13–75)	22 (150)
21	5005	-O, -H12, -H14, -H16, -H18, -H22, -H24, -H26, -H32, -H34, -H36, -H38, -H112, -F	All	Up through 3.000 (75)	15 (105)
21	5050	-O, -H22, -H24, -H26, -H32, -H34, -H36, -H38, -H112, -F	All	Up through 3.000 (75)	18 (125)
22	5052	-O, -H22, -H24, -H26, -H28, -H32, -H34, -H36, -H38, -H112, -F	All	Up through 3.000 (75)	25 (170)
25	5083	-O, -H111, -H112	Forgings	Up through 4.000 (100)	38 (262)
		-O, -H111, -H112, -F	Extrusions	Up through 5.000 (125)	39 (270)
		-O, -H112, -H116	Sheet and plate	0.051–1.500 (1–38)	40 (270)
		-H321,-F	Plate	1.501–3.000 (38–75)	39 (270)
		-O, -F	Plate	3.001–5.000 (75–125)	38 (262)
				5.001–7.000 (125–175)	37 (255)
				7.001–8.000 (175–200)	36 (248)
25	5086	-O, -H32, -H34, -H36, -H38, -H111, -H112, -H116, -F	All	Up through 2.000 (50)	35 (240)
		-O, -H111, -H112, -F	Extrusions	2.001–5.000 (50–125)	35 (240)
			Plate	2.001–3.000 (50–75)	34 (235)
22	5154	-O, -H22, -H24, -H26, -H28, -H32, -H111, -H112, -F	All	Up through 3.000 (75)	30 (205)
22	5254	-O, -H32, -H34, -H36, -H38, -H112	All	0.051–3.000 (1–75)	30 (205)
22	5454	-O, -H32, -H34, -H111, -H112, -F	All	Up through 3.000 (75)	31 (215)

(Continued)

Table 5.16 (Continued)
Strength of Welded Aluminum Alloys (GTAW or GMAW with No Postweld Heat Treatment)

Material Group No.	Alloy	Temper	Product	Thickness Range, in. (mm)	Minimum Tensile Strength, ksi (MPa)
25	5456	-O, -H111, -H112, -F	Extrusions	Up through 5.000 (125)	41 (285)
		-O, -H112, -H116,	Sheet and plate	0.051–1.500 (1–38)	42 (285)
		-H321, -F	Plate	1.501–3.000 (38–75)	41 (285)
		-O, -H116, -F		3.001–5.000 (75–125)	40 (270)
		-O, -F		5.001–7.000 (125–175)	39 (270)
				7.001–8.000 (175–200)	38 (262)
22	5652	-O, -H22, -H24, -H32, -H34, -H112, -F	All	Up through 3.000 (75)	25 (170)
23	6005	-T5	Extrusions	Up through 1.000 (25)	24 (165)
23	6061	-T4, -T42, -T451, -T51, -T6, -T62, -T651	All	Up through 3.000 (75)	24 (165)
		-T6, -T62, -T651	Plate and forgings	3.001–4.000 (75–100)	24 (165)
		-T62, -T651	Plate	4.001–6.000 (100–150)	24 (165)
		-T6	Forgings	4.001–8.000 (100–200)	24 (165)
23	Alclad 6061	-T4, -T42, -T451, -T6, -T62, -T651	Sheet and plate	Up through 3.000 (75)	24 (165)
		-T62, -T651	Plate	3.001–5.000 (75–125)	24 (165)
23	6063	-T4, -T42, -T5, -T52, -T6, -T62, -T83, -T831, -T832	Extrusions	Up through 1.000 (25)	17 (115)
23	6351	-T4, -T5, -T51, -T53, -T54, -T6	Extrusions	Up through 1.000 (25)	24 (165)
27	7005	-T53	Extrusions	0.125–1.000 (3–25)	40 (270)
26	A201.0	-T7	Castings	All	See note
26	354.0	-T61, -T62	Castings	All	See note
26	C355.0	-T6, -T61	Castings	All	See note
26	356.0	-T6, -T7, -T71	Castings	All	23 (159)
26	A356.0	-T6, -T61	Castings	All	See note
26	357.0	-T6, -T7	Castings	All	See note
26	A357.0	-T6, -T61	Castings	All	See note
26	359.0	-T61, -T62	Castings	All	See note
26	443.0	-F	Castings	All	17 (115)
26	A444.0	-T4	Castings	All	17 (115)
26	514.0	-F	Castings	All	22 (150)
26	535.0	-F	Castings	All	35 (240)

Note: Minimum as-welded tensile strength has not been established for this alloy. The tensile properties must be established by procedure qualification and approved by the engineer.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 1997. *Structural Welding Code—Aluminum*, ANSI/AWS D1.2-97, Miami: American Welding Society, Table 4.2.

With the proper choice of filler metal, a weldment fabricated from a heat-treatable aluminum alloy can be solution-heat treated and aged after welding. The welded assembly will regain full strength with some loss in ductility. Although this is the best method of providing maximum weld strength, it is usually uneconomical or impractical. The cost of heat treatment can be high, especially if a large furnace is required, and the quenching operation may result in unacceptable distortion of the product.

At times, it may be practical to weld a heat-treatable alloy in the solution-treated condition and then age it after welding. This can increase the strength of the weld and heat-affected zone as compared to that achieved in the as-welded condition. This procedure also prevents the distortion problem associated with solution heat treating. No method exists to overcome softening in nonheat-treatable alloys other than further cold working of the parts after welding, which is seldom practical. The weakest location in an as-welded assembly is the annealed (or partially annealed) heat-affected zone.

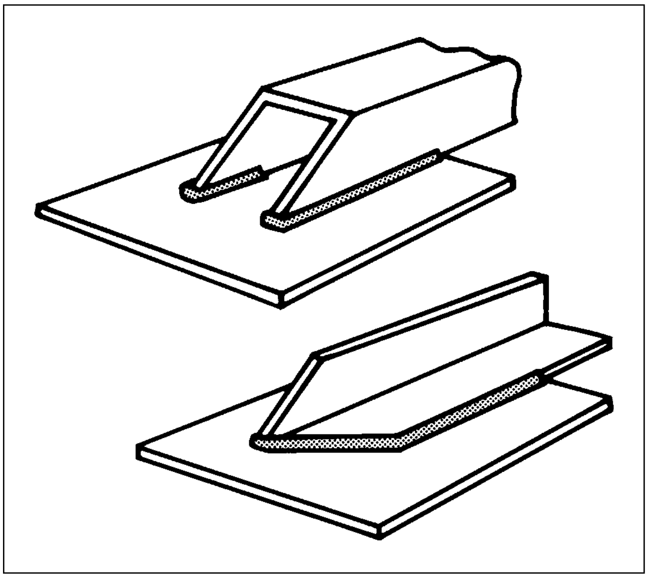


Figure 5.53—Beveling or Sniping the End of a Member to Reduce Stress Concentration at End of Connection

STRESS DISTRIBUTION

When welds located in critical areas do not cover the entire cross section, the strength of the section depends on the percentage of the cross-sectional area affected by the heat of welding. When members must be joined at locations of high stress, the welds should be parallel to the principal member and to the main stress in that member. Transverse welds in tension members should be avoided.

Welds are frequently more highly stressed at the ends than in the central portions. To avoid using thicker sections, areas of high stress in welds can be minimized by sniping. This consists of beveling the end of a member to limit the concentration of stress in the weld at that end. The weld should wrap around the end of the member, however. This type of member termination is illustrated in Figure 5.53.

In many weldments, it is possible to locate the welds where they will not be subjected to high stresses. It is frequently possible to make connections between a main member and accessories such as braces by welding at the neutral axis or another point of low stress.

SHEAR STRENGTH OF FILLET WELDS

The shear strength of fillet welds is controlled by the composition of the filler metal. The use of a high-strength filler metal permits smaller welds. The highest strength filler metal is alloy 5556. Typical shear strengths of longitudinal and transverse fillet welds made with several aluminum filler metals are shown in Figures 5.54 and 5.55, respectively.

Assume, for example, that a longitudinal fillet weld having a strength of 4000 lb/in. (700 kN/m) is desired. If 5356 filler metal is used, a 1/4 in. (6 mm) fillet weld can be applied in a single pass. However, 4043 filler metal would require a 3/8 in. (9 mm) fillet weld that would probably require three passes to deposit. The use of the stronger filler metal has an obvious economic advantage as it results in lower labor and material costs.

The minimum practical size of a fillet weld depends on the thickness of the base metal and the welding process and procedure used. Minimum recommended fillet weld sizes are shown in Table 5.17. When minimum weld sizes must be used, a filler metal with the lowest suitable strength for the applied load should be selected to take advantage of the ductility of the weld metal.

By applying the appropriate safety factor to the shear strength of weld metal, the designer can determine the allowable shear stress in a fillet weld. Appropriate factors of safety and allowable shear stresses in fillet welds for aluminum structures are given in the *Aluminum Design Manual: Specifications and Guidelines for Aluminum Structures*.[59]

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59. See Reference 55.

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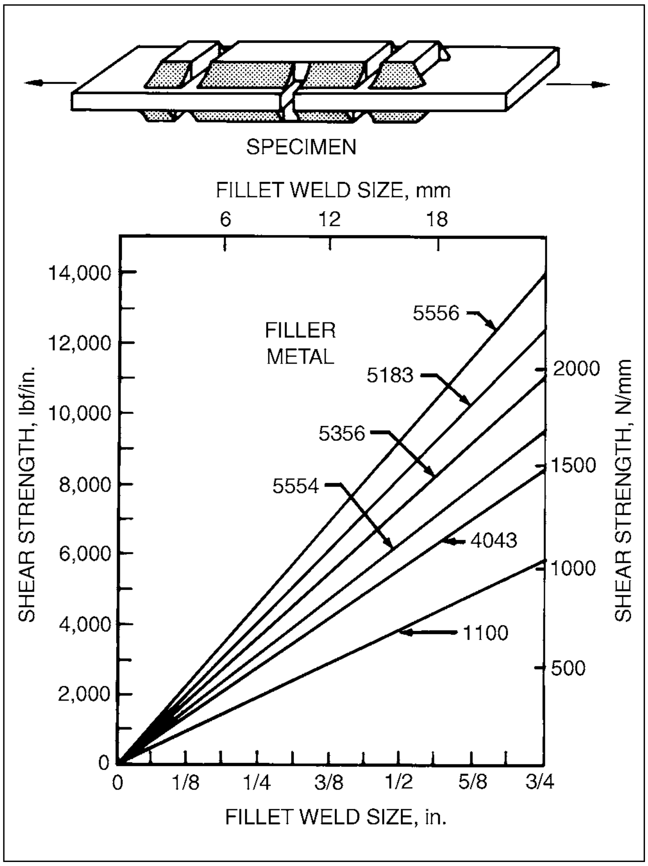

Figure 5.54—Typical Shear Strengths of Longitudinal Fillet Welds with Various Aluminum Filler Metals

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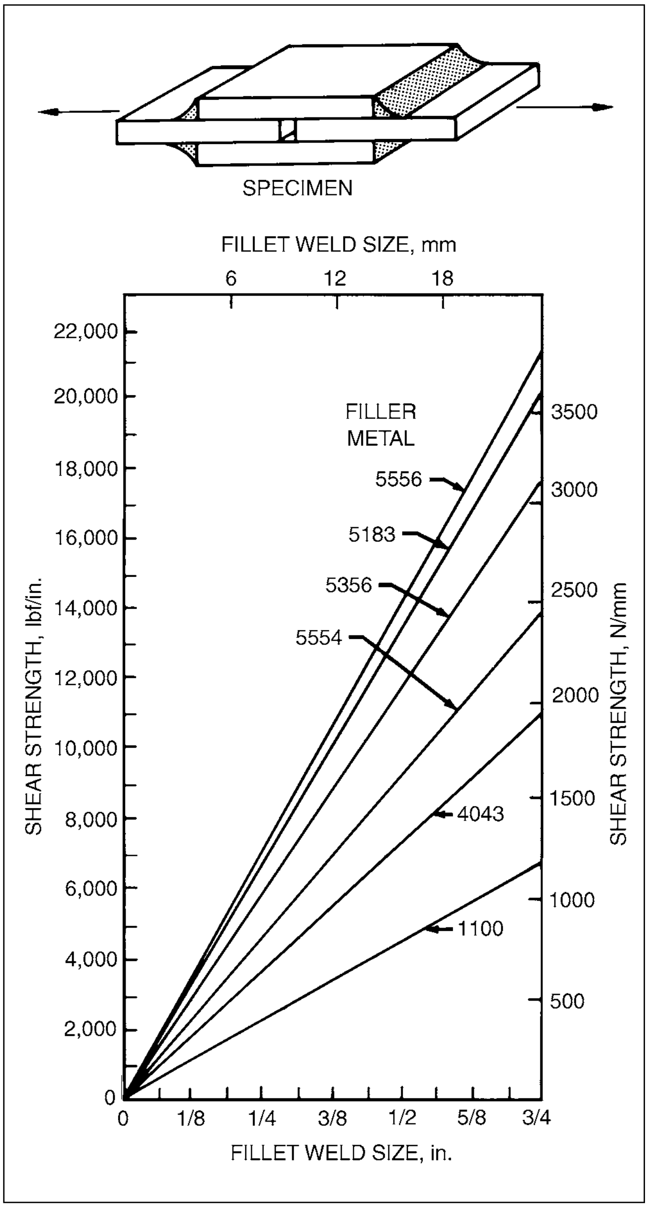

Figure 5.55—Typical Shear Strengths of Transverse Fillet Welds with Various Aluminum Filler Metals

FATIGUE STRENGTH

The fatigue strength of welded aluminum structures follows the same general rules that apply to fabricated assemblies made of other metals.[60] However, aluminum does not have an endurance limit like steel does. Therefore, when fatigue governs the design, the common solution is to reduce the stress by increasing the natural cross section. Fatigue strength is governed by the peak stresses at points of stress concentration rather than by nominal stresses. Eliminating stress raisers to reduce the peak stresses tends to increase the fatigue life of the assembly.

The average fatigue strengths of as-welded joints in small-scale specimens of four aluminum alloys are shown in Figure 5.56. These results are for butt joints in 3/8 in. (9 mm) plate welded by the gas metal arc welding process. The specimens were welded on one side, backgouged, and then backwelded. The stress ratio of zero signifies that the tensile stress increased from zero to the plotted value and returned to zero during each cycle.

60. Fatigue data for welded aluminum joints are given in Appendix A of Sharp, M. L., G. E. Nordmark, and C. C. Menzemer, 1996, *Fatigue Design of Aluminum Components and Structures*, New York: McGraw Hill.

Table 5.17
Minimum Fillet Weld Size (Aluminum)

Base Metal Thickness of Thicker Part Joined (T)		Minimum Size of Fillet Weld*		
in.	mm	in.	mm	
T ≤ 1/4	T ≤ 6	1/8†	3	Single-pass welds must be used
1/4 < T ≤ 1/2	6 < T ≤ 13	3/16	5	
1/2 < T	13 < T	1/4	6	

*Except that the weld size need not exceed the thickness of the thinner part joined. For this exception, particular care should be taken to provide sufficient preheat to ensure weld soundness.
† Minimum size for dynamically loaded structures is 3/16 in. (5 mm).

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 1997, *Structural Welding Code—Aluminum*, ANSI/AWS D1.2-97, Miami: American Welding Society, Table 2.2.

The effect of the stress ratio on fatigue life is illustrated in Figure 5.57. This behavior is typical for all metals.[61]

The fatigue strengths of the various aluminum alloys are markedly different. Below 10^4 cycles, designers may prefer to use one alloy rather than another for a particular application. However, beyond 10^6 cycles, the differences among various alloys are minimal. The solution to fatigue problems beyond the range of 10^6 cycle involves a change of design rather than a change of alloy.[62, 63]

Designers should utilize symmetry in the assembly for balanced loading. Sharp changes in direction, notches, and other stress raisers should be avoided. The fatigue strength of a groove weld may be increased significantly by removing weld build-up or crown or by peening the weldment. If these procedures are not practical, the weld build-up or crown should blend smoothly into the base metal to avoid abrupt changes in thickness. With welding processes that produce relatively smooth weld beads, little or no increase in fatigue strength is gained by smoothing the weld faces. It should be noted that the benefit of smooth weld beads can be nullified by excessive spatter during welding. Spatter deposits sometimes create severe stress raisers in the base metal adjacent to the weld.

While the residual stresses produced by welding are not considered to affect the static strength of aluminum, they can be detrimental in regard to fatigue strength.

61. Dieter, G., 1961, *Mechanical Metallurgy,* New York: McGraw Hill.
62. See Reference 55.
63. Comparison of design codes and specifications are given in Chapter 12 of Sharp, M. L., G. E. Nordmark, and C. C. Menzemer, 1996, *Fatigue Design of Aluminum Components and Structures,* New York: McGraw Hill.

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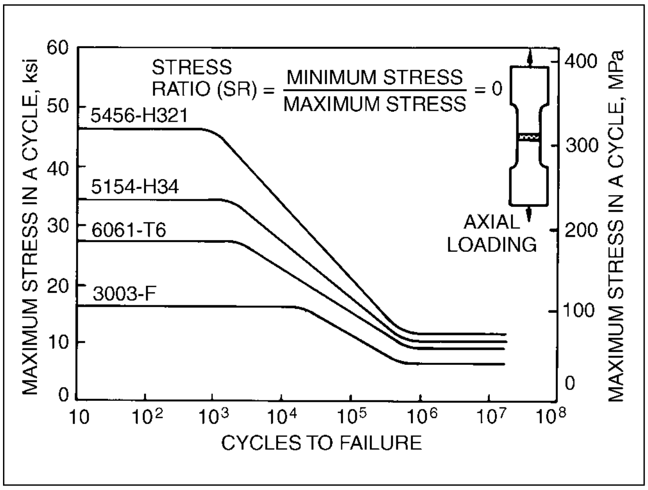

Figure 5.56—Fatigue Test Results of Butt Joints in Four Aluminum Alloys, 3/8 in. Thick Gas Metal Arc Welded Plates

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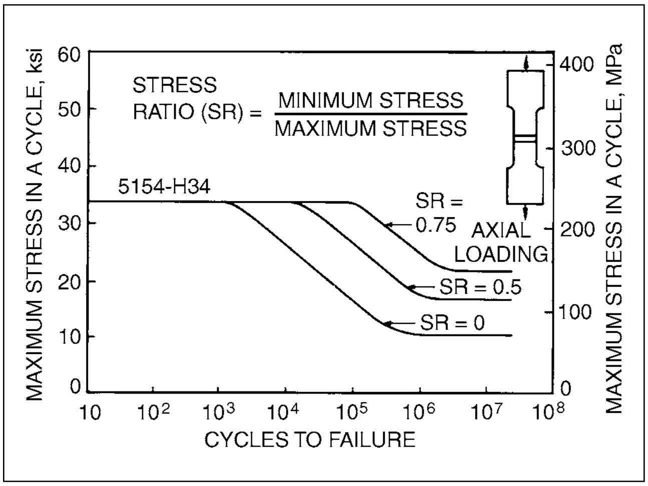

Figure 5.57—Effect of the Stress Ratio (SR) on the Fatigue Life of a 5154-H34 Aluminum Weldment

Several methods can be employed to reduce residual welding stresses. These include shot peening, multiple-pin gun peening, thermal treatments, and the hydrostatic pressurizing of pressure vessels beyond the yield strength. Shot peening or hammer peening is beneficial when it changes the residual stresses at the weld face from tension to compression for a depth of 0.005 in. to 0.030 in. (0.1 mm to 0.8 mm).

However, current design codes for fatigue in civil structures have focused on utilizing only joint details

Table 5.18
Minimum Tensile Strengths of Arc Welded Butt Joints in Aluminum Alloys at Various Temperatures

Base Metal-Alloy Designation	Filler Metal	Ultimate Tensile Strength, ksi*					
		–300°F	–200°F	–100°F	100°F	300°F‡	500°F†
2219-T37‡	2319	48.5	40.0	36.0	35.0	31.0	19.0
2219-T62§	2319	64.5	59.5	55.0	50.0	38.0	22.0
3003	ER1100	27.5	21.5	17.5	14.0	9.5	5.0
5052	ER5356	38.0	31.0	26.5	25.0	21.0	10.5
5083	ER5183	54.5	46.0	40.5	40.0	—	—
5083	ER5356	48.0	40.5	35.5	35.0	—	—
5454	ER5554	44.0	37.0	32.0	31.0	26.0	15.0
5456	ER5556	56.0	47.5	42.5	42.0	—	—
6061-T6‡	ER4043	34.5	30.0	26.5	24.0	20.0	6.0

*To convert to MPa, multiply ksi by 6.895 (ksi value).
† Alloys not listed at 300°F (150°C) and 500°F (260°C) are not recommended for use at sustained operating temperatures of over 150°F (65°C).
‡ As welded.
§ Heat treated and aged after welding.

and stress ranges, rather than stress ratio, as essential criteria. An overview and a comparison of current codes are presented in Sharp, Nordmark, and Menzemer.[64]

Thermal treatments to relieve residual stresses are beneficial. They increase fatigue resistance and provide dimensional stability during subsequent machining. Thermal treatments for nonheat-treatable alloys such as the 5000 series can relieve up to 80% of the residual welding stresses with little decrease in the static strength of the base metal. Heat-treatable alloys are not as well suited to thermal treatments for the relief of residual stresses because temperatures that are high enough to cause a significant reduction in residual stress may also substantially diminish strength properties. However, a reduction in residual welding stresses of about 50% is possible if a decrease in strength of approximately 20% can be tolerated.

EFFECT OF SERVICE TEMPERATURE

The minimum tensile strengths of aluminum arc welds at various temperatures are presented in Table 5.18. The performance of welds in nonheat-treatable alloys closely follows that of annealed base metals.

Most aluminum alloys lose a substantial portion of their strength at temperatures above 300°F (150°C). Certain alloys, such as 2219, have better elevated-temperature properties, but their applications have definite limitations. With a magnesium content of 3.5% or higher, the 5000 series alloys are not recommended for use at sustained temperatures above 150°F (65°C). Alloy 5454, with its comparable filler metal ER5554, is the strongest of the 5000 series alloys recommended for applications such as hot chemical storage containers and tank trailers.

In summary, aluminum is an ideal material for low-temperature applications. Most aluminum alloys have high ultimate and yield strengths at temperatures below room temperature. The 5000 series alloys possess good strength and ductility at very low temperatures along with good notch toughness. Alloys 5083 and 5456 are used extensively in pipelines, storage tanks, and marine vessel tankage for the handling of cryogenic liquids and gases.

CONCLUSION

Many issues are related to the process of designing for welding. In addition to component performance, service, intended life, and safety, the designer should have a good understanding of the fundamentals of welding, metallurgy, fabrication technology, and inspection techniques.

Although this chapter is quite lengthy, it is not intended to be comprehensive. Many industry specific

64. Sharp, M. L., G. E. Nordmark, and C. C. Menzemer, 1996, *Fatigue Design of Aluminum Components and Structures,* New York: McGraw Hill.

issues—codes, specifications, contract documents, inspection standards, and associated acceptance criteria—must be addressed when designing weldments. The reader is therefore advised to seek additional technical knowledge in the particular field of interest.

This chapter has been adapted, with permission of The Lincoln Electric Company, from "Designing for Arc Welding," Section 2 of The Lincoln Electric Company, 1995, *The Procedure Handbook of Arc Welding,* 13th ed., Cleveland: The Lincoln Electric Company.

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65. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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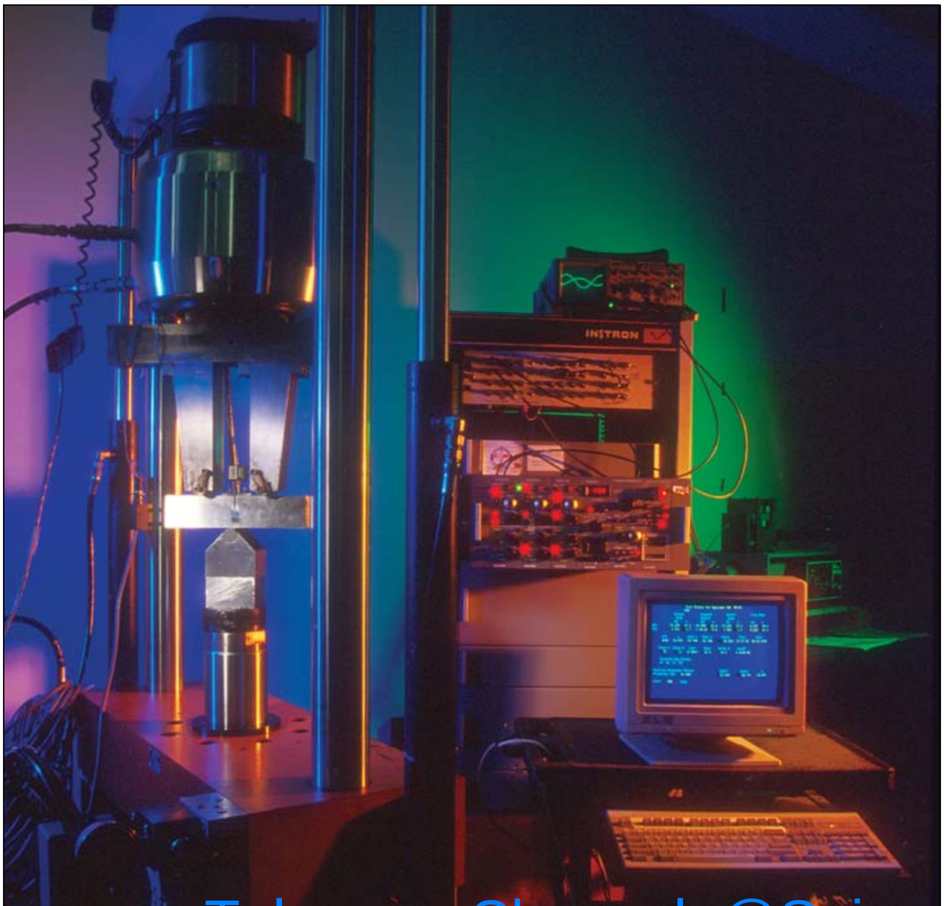
CHAPTER 6

TEST METHODS FOR EVALUATING WELDED JOINTS



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CHAPTER 6

TEST METHODS FOR EVALUATING WELDED JOINTS

INTRODUCTION

All types of welded structures—from steel bridges to jet components—serve a function. Likewise, the welded joints in these structures and components are designed for service-related capabilities and properties. Predicting service performance on the basis of laboratory testing presents a complex problem because weld size, configuration, and the environment as well as the types of loading to which weldments are subjected differ from structure to structure. This complexity is further increased because welded joints—consisting of unaffected base metal, weld metal, and a heat-affected zone (HAZ)—are metallurgically and chemically heterogeneous. In turn, each of these regions is composed of many different metallurgical structures as well as chemical heterogeneities.

Testing is usually performed to ensure that welded joints can fulfill their intended function. The ideal test, of course, involves observing the structure in actual or simulated service. An example of such "mock-up" testing is that done to validate new designs of moment frame and similar connections for large buildings in strong seismic areas.[1] Unfortunately, mock-up and actual service tests are expensive, time consuming, and potentially hazardous. Therefore, standardized tests and testing procedures are performed in the laboratory to compare a specimen's results with those of metals and structures that have performed satisfactorily in service. Standardized testing provides a bridge between the properties assumed by designers and analysts and those exhibited by the actual structure.

Mechanical testing provides information on the mechanical or physical properties of a small sample of welds or metals to infer the properties of the remaining material within a lot, heat range, or welding procedure. Standardized procedures are used to sample, orient, prepare, test, and evaluate the specimens in order to provide results that can be compared to design criteria. For example, virtually all design codes are based on a minimum tensile strength that must be achieved not only in the base metal but also in the weldment.

When selecting a test method, the test's purpose must be considered and balanced against the amount of time and the resources available. For example, tension and hardness tests both provide a measure of strength, but the latter are simpler and more economical to perform. Hardness tests can be used to confirm that adequate strength has been achieved in some heat-treated components. Although they can verify that a maximum heat-affected-zone hardness has not been exceeded, hardness tests cannot adequately establish the strength of a welded joint because of the heterogeneous nature of welds. Regardless of the differences between test methods, all testing procedures measure either a composite average or a "weak-link" component of the property of interest within the area sampled. Thus, an understanding of the test details is necessary to interpret the results.

When testing a welded or brazed joint, the investigator must not only relate the test to the intended service of the actual structure but also determine whether true properties are measured by the limited region tested.

1. American Institute for Steel Construction (AISC), *Seismic Provisions for Structural Steel Buildings,* Chicago: American Institute for Steel Construction.

Test results must therefore be carefully interpreted and applied. As each laboratory test provides only a limited amount of information on the properties of welded joints, most weldments are evaluated using several tests. Each test provides specific data on the serviceability of the weldment. The properties evaluated by testing include strength (e.g., ultimate tensile strength, yield strength, shear strength), tensile ductility (e.g., elongation and reduction of area), bend test ductility, toughness (e.g., fracture toughness, crack arrest toughness, and Charpy V-notch toughness), fatigue, corrosion, and creep. The scope of the testing is either defined as part of the investigation or specified in the relevant code or standard, depending on the application.

Testing should be performed on samples that reflect the heat treatment condition used in service. However, the topic of the aging of steel specimens often arises in testing welded joints. In this context, aging is a degassing treatment at room temperature or a slightly elevated temperature. For example, the American Welding Society's filler metal specification for carbon steel flux cored arc welding electrodes,[2] as well as some welding codes such as *Structural Welding Code—Steel*, AWS D1.1:2000,[3,4] permit the aging of tension test specimens at 200°F to 220°F (93°C to 104°C) before testing. However, other codes such as the *Bridge Welding Code*, ANSI/AASHTO/AWS D1.5-96,[5] do not permit aging for weld procedure qualification tests.

The welding process can introduce hydrogen into the weld metal, mostly from water that is disassociated under the high temperature of the arc. The hydrogen diffuses out over time but may introduce anomalies into tensile test results. These can sometimes be seen as "fisheyes" (small pores surrounded by a round, bright area on the fracture surface of tension tests of steel welds) even though normal cup-and-cone fracture may be observed, if tested only days later, and the yield strength, ultimate strength, and impact test results will remain unchanged. Such low-temperature aging is permitted because it does not change the metallurgical structure; it simply quickens the diffusion of hydrogen from the weldment. With this one exception, weldment testing is typically performed using specimens that represent the heat treatment condition of the weldment as it will be used in service.

The various testing methods used to evaluate the expected performance of welded and brazed joints and thermal spray applications are examined in this chapter. The description of each method includes a discussion of the property being tested, the test methods used, the application of results, and, most importantly, the manner in which these results relate to welded joints. An overview of weldability testing is also presented.[6]

This chapter makes frequent reference to the *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0 and AWS B4.0M,[7] and *Standard Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A 370.[8] The latest edition of these standards should be consulted for more information on the testing and evaluation of welded joints. In addition, the American National Standard *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1,[9] should be consulted for rules regarding health and safety precautions.

TESTING FOR STRENGTH

The design of nearly every component and structure is based on minimum tensile properties. As welded joints contain metallurgical and often compositional differences that result from the welding process, the effects of these changes on the mechanical properties of the weldment must be assessed. Some strength tests, such as tension tests, measure tensile strength directly, while others, such as the peel test, verify that the weld is as strong as the base metal. The various techniques used to evaluate the strength of weldments are discussed below.

2. American Welding Society (AWS) Committee on Filler Metals, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*, ANSI/AWS A5.20, Miami: American Welding Society.
3. American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society.
4. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
5. American Welding Society (AWS) Committee on Structural Welding, 1996, *Bridge Welding Code,* ANSI/AASHTO/AWS D1.5-96, Miami: American Welding Society.
6. Weld soundness is evaluated using the nondestructive examination methods described in Chapter 14 of this volume.
7. American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0, Miami: American Welding Society; American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds,* AWS B4.0M, Miami: American Welding Society.
8. American Society for Testing and Materials (ASTM) Subcommittee A01.13, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A 370, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
9. American National Standards Institute (ANSI) Accredited Standards Committee Z49, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1, Miami: American Welding Society.

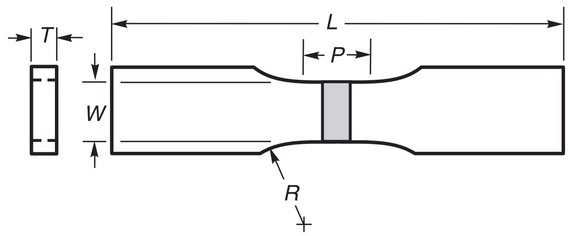
TENSION TESTS

Tension tests are conducted to evaluate the strength and ductility of the base metal, the weld metal, and the weldment. These tests provide quantitative data for the analysis and design of welded structures. Tension tests are frequently conducted to verify that the tensile strength of a weldment meets specified minimum values.

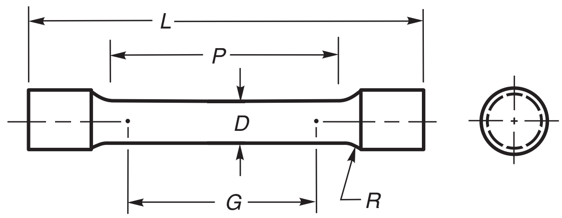
Fundamentals

Tension testing involves the loading of specimens in tension until failure occurs. These tests provide information about two strength values—yield strength and ultimate tensile strength—along with two measures of ductility—elongation and the reduction of area. All these properties are often reported for the base material from tests performed by the manufacturer of the material. The modulus of elasticity (Young's modulus) can also be determined from the tensile test, although this property does not vary significantly for a given material and is not typically reported.

Tension Test Specimens. The various types of tension tests differ primarily with respect to the orientation of the test specimen within the weldment or structure. For example, in the uniaxial tension test used in weldment and base metal evaluation, specimens have either a circular ("round") or rectangular ("strap") cross section within a reduced gauge length. Two typical specimen configurations are illustrated in Figure 6.1.



(A) Rectangular Tensile Specimen



(B) Round Tensile Specimen

Key:
- T = Thickness of the reduced section (rectangular), in. (mm)
- W = Width of the reduced section (rectangular), in. (mm)
- D = Diameter of the reduced section (round), in. (mm)
- L = Specimen length, in. (mm)
- R = Radius, in. (mm)
- P = Parallel ("reduced") section
- G = Gauge length, in. (mm)

Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 1998, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0-98, Miami: American Welding Society, Figures A11 and A12.

Figure 6.1—Typical Tensile Specimens: (A) Rectangular and (B) Round

Test Procedure. The specimen ends, which may be plain, threaded, or grooved depending on the particular grips used, are placed within the two grips of a tension machine. The grips are then moved away from each other, placing the specimen in uniaxial tension while the load placed on the specimen is monitored or recorded. Only the maximum load is required to define the ultimate tensile strength (UTS) (see below).

Data Collection and Interpretation. Simultaneous recording of both the applied load and the resulting specimen displacement (i.e., lengthening) within the gauge length is necessary to determine the yield strength and define the stress-strain curve. The engineering stress-strain curve is developed by plotting the instantaneous load divided by the original cross-sectional area of the test specimen against the instantaneous displacement (within the gauge length) divided by the original gauge length of the specimen. A stress-strain curve for low-carbon steel is presented in Figure 6.2.

As can be observed in Figure 6.2, stress-strain diagrams provide information on (1) the ultimate tensile strength, (2) the yield point, (3) offset yield strength, and (4) the modulus of elasticity. The percent elongation and percent reduction can also be determined with the test.

For engineering applications, the term *ultimate tensile strength (UTS)* is defined as the maximum load divided by the original cross-sectional area of the specimen. The maximum load can be taken directly from the tension testing machine load pointer. Alternatively, it can be derived from the peak of the stress-strain curve after yielding. It should be noted that the maximum load is not typically the load at fracture, which is usually lower because extensive local yielding has significantly reduced the cross-sectional area of the specimen. The elongation of the specimen is distributed nearly uniformly over the reduced section until the maximum load is reached, but it becomes increasingly local as necking occurs.

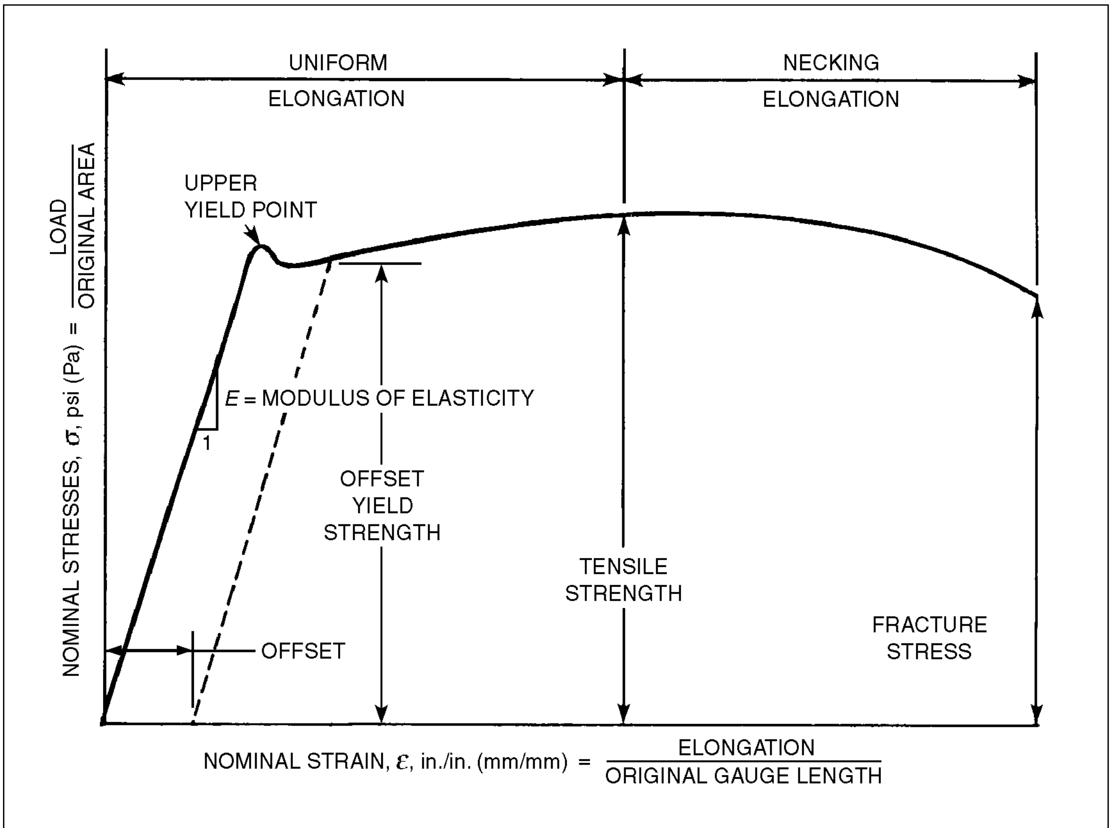


Figure 6.2—Engineering Stress-Strain Curve for Low-Carbon Steel

The yield strength, an arbitrarily defined measure, is intended to indicate the stress beyond which permanent deformation occurs. The stress-strain curve of some materials exhibits a well-defined upper yield point that clearly marks the end of fully elastic behavior, and stresses above this point permanently elongate the material. The initial straight portion of the curve has a slope equal to the modulus of elasticity. The upper yield point is followed by yielding at a constant, slightly lower load (the lower yield point), after which the curve rises again due to work hardening. However, arbitrary definitions of yield strength are necessary because some materials do not exhibit a clear yield point.

The offset yield strength is determined by constructing a line that is parallel to the elastic, straight part of the curve (i.e., with a slope of the modulus of elasticity) but offset along the strain axis by 0.2% strain. The stress at the intersection of this offset line and the stress-strain curve is the 0.2% offset yield strength. The 0.2% offset method, the most commonly used for weldment testing, is shown in Figure 6.2. A less common method involves the use of the stress at a specific strain, such as the 0.5% total strain yield strength. This method does not require a stress-strain curve, but assumes a specific stress-strain relationship. For this reason, it is less accurate and generally unreliable.

The percent elongation is the ratio of the increase in gauge length to the original gauge length. The final gauge length is measured after fitting the broken halves of the specimen together. The percent elongation includes uniform strain, which depends on the original gauge length, and local or necking strain, which is affected by the specimen geometry. Therefore, elongation percentages should be compared to those for identical specimens only.

The percent reduction of area is determined by the ratio of the decrease in cross-sectional area after fracture to the original cross-sectional area. The reduction in area is caused by this "necking" of the specimen perpendicular to the loading axis due to plastic flow. The final area is determined after fitting the broken halves together by measuring the diameter or width and thickness.

Specimen Geometry. As noted above, the percentage of elongation that occurs during testing depends significantly on the specimen geometry. Standard round bar test specimens have a specific relationship between the gauge length and the diameter of the reduced section; this is generally a ratio of 4 to 1. However, all significant dimensions of tensile specimens are standardized because the shape of the specimen can also affect the results.

Figure 6.3 shows the fracture surface for two tensile specimens taken from the same material and tested at the same strain rate. The specimen on the right is visibly necked and shows good ductility in a classic "cup-and-cone" fracture. The specimen on the left was machined to the same initial diameter, but with a V-groove, not a smoothly transitioned reduced section. This specimen exhibited higher yield strength but virtually no ductility. Steels have significant notch sensitivity, which affects the apparent yield and ductility. This must be taken into consideration when designing components with sharp changes in sectional area.

Detailed information on specimen preparation and test procedures for tension tests is presented in *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A 370.[10]

Photograph courtesy of Douglas E. Williams, P.E.

Figure 6.3—Effect of a Notch on Tensile Ductility

Base Metal Tension Tests

The strength and ductility of base metals are generally obtained by conducting a simple uniaxial tension test. The strength characteristics of base metals are typically determined at the producing mill and reported on the material test report. Such tests for steel products are typically performed in accordance with *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A 370.[11] Tension testing of the base metal during weld procedure qualification is sometimes performed using similar methods to verify reported data.

Base metal tension tests are most commonly performed in one of two orientations: longitudinal or transverse. Longitudinal specimens have the long axis oriented parallel to the rolling direction, whereas transverse specimens are oriented perpendicular to the rolling direction. The orientation of the specimen is the only difference, and both longitudinal and transverse specimens are generally prepared and tested as standard uniaxial tension tests.

The offset yield strength, ultimate strength, percent elongation, and sometimes the percent reduction in area are reported. It is common to test two specimens for each sampled location. Figure 6.4 depicts typical stress-strain curves for several commercial steels, ranging from mild steel (ASTM A 36) to high-strength structural steels (ASTM A 514 and A 517). It should be noted that a distinct upper yield point does not always occur.

A third orientation, the through-thickness direction, is most often used to determine the susceptibility of a rolled product to lamellar tearing, not strength. Steels susceptible to lamellar tearing resulting from welding have poor reduction of area in tensile specimens taken in the through-thickness direction. The specimens are prepared by welding extensions on either side of a plate or other rolled product and then machining them into round tensile specimens with the region of interest within the gauge length, as described in *Standard Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications,* ASTM A 770/A 770M.[12]

Weld Tension Tests

Because weld test sections are heterogeneous—containing weld, HAZ, and unaffected base metals—the tension testing of welds is somewhat more complex than the testing of the base metal. To obtain an accurate assessment of weld strength and ductility, several differ-

10. See Reference 8.
11. See Reference 8.

12. American Society for Testing and Materials (ASTM) Subcommittee A01.11, *Standard Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications,* ASTM A 770/A 770M, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

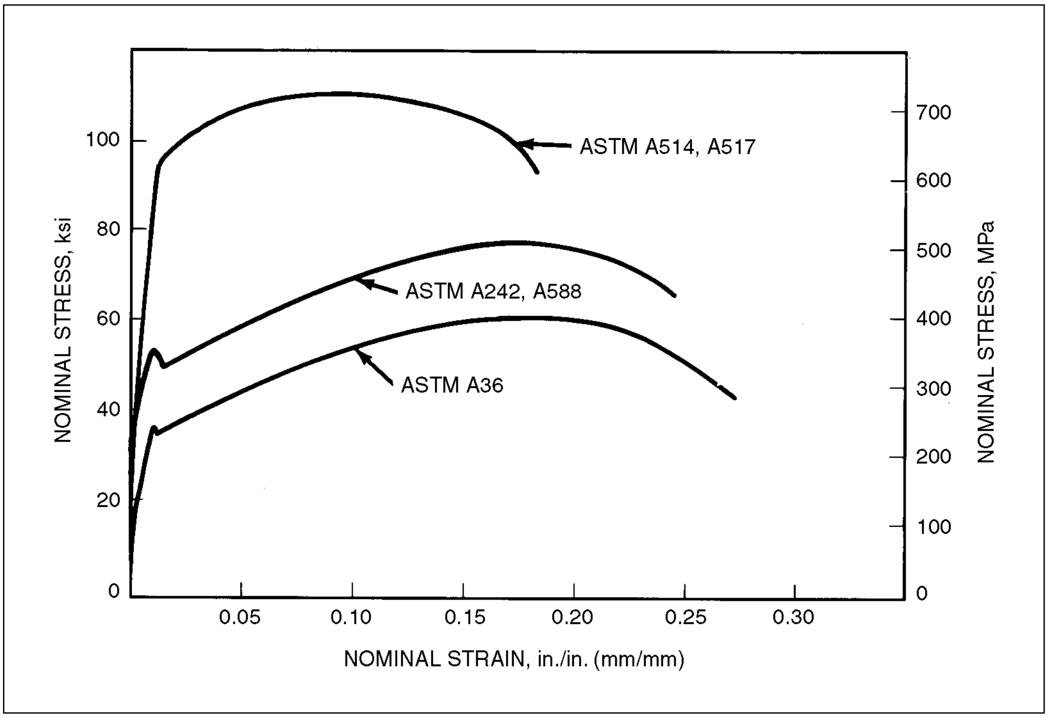


Figure 6.4—Nominal Stress-Nominal Strain Curves for Various Steels

ent specimens and orientations must be used, depending on whether the properties of the weld metal or the weldment are of interest.

Rectangular specimens with the full test-piece thickness are generally used to evaluate the strength of the composite weldment, as shown in Figure 6.5. Specimens can be taken either transverse or parallel (longitudinal) to the weld. However, weld procedure qualification tests normally use the transverse configuration, partly because the properties in the transverse direction are more sensitive to welding procedure variables. For rectangular weld specimens, the full test-piece thickness is typically tested, and in some cases, the weld reinforcement is left intact on the test specimen to reflect the properties of the weldment.

All-Weld-Metal Test. The all-weld-metal tension test is used to determine the tensile strength, yield strength, elongation, and reduction area of the weld metal. In this test, the specimen is oriented parallel to the weld axis, and the entire specimen is machined from weld metal. The chemical composition of the weld metal is affected by dilution from the base metal, so joint preparation can affect the results.

When testing to determine the properties of the weld metal in a particular weldment, the welding process and procedure to be used in production should be used to make the test weld.[13] When this test is conducted to qualify a filler metal, a standardized weld joint configuration that minimizes the effect of base metal dilution is used. This procedure is described in filler metal specifications, such as *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding,* ANSI/AWS A5.1.[14]

Longitudinal Weld Test. In the longitudinal weld test, the test specimen is loaded parallel to the weld axis. The reduced cross section of the specimen contains weld metal, heat-affected-zone metal, and base metal. During testing, all three zones are forced to strain equally and simultaneously. The weld metal, regardless of strength, elongates with the base metal until failure occurs. Low ductility of the weld metal or heat-affected zone may initiate fracture at strength levels below that of the base metal.

The longitudinal weld test provides information solely on the ultimate tensile strength of weldments.

13. See, for example, Figure 4.23 in American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society.
14. American Welding Society (AWS) Committee on Filler Metals, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding,* ANSI/AWS A5.1, Miami: American Welding Society.

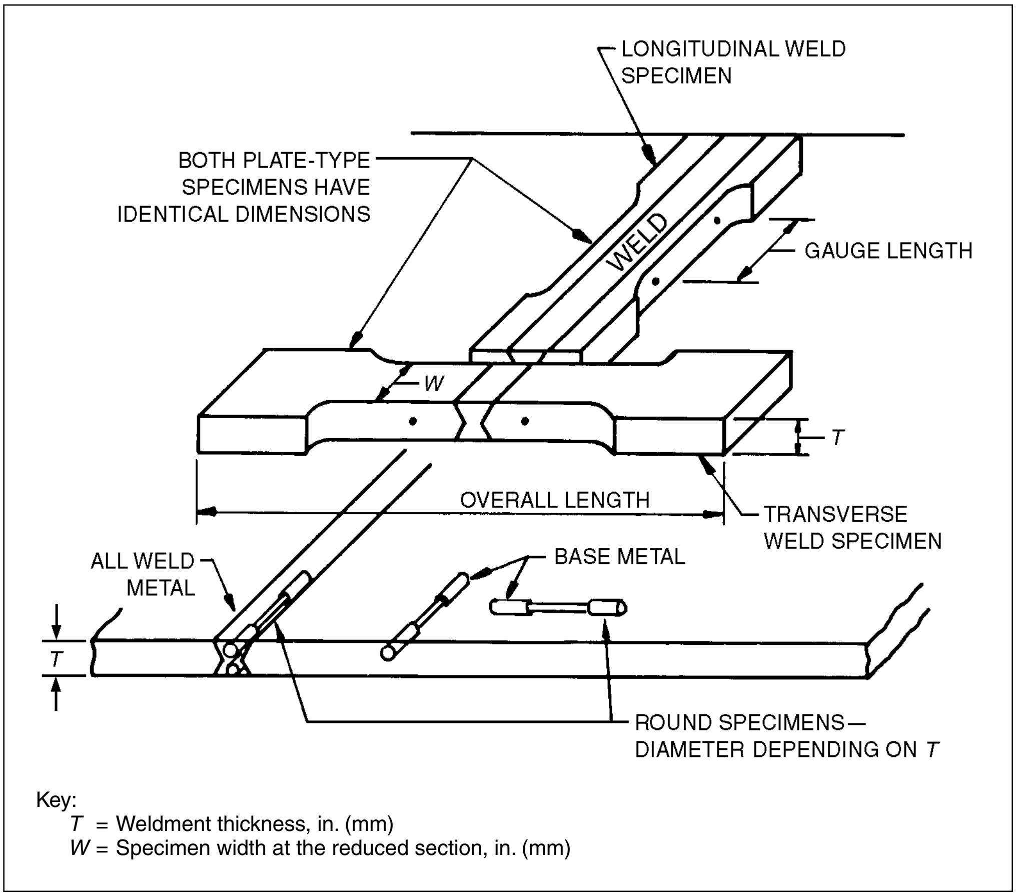


Figure 6.5—Typical Tension Test Specimens for the Evaluation of Welded Joints

However, elongation may be measured as an indication of the ductility of the joint.

Transverse Weld Test. A transverse weld specimen is tested to facilitate the interpretation of test results for a complete welded joint. The reduced section of the specimen, typically centered on the weld, contains base metal, heat-affected zones, and weld metal. When all of these are simultaneously subjected to the same stress during testing, the zone with the lowest strength tends to elongate and break first. For example, if the weld metal has higher strength than that of the unaffected base metal, failure will occur outside the weld area. In this case, this test would provide no quantitative information about the strength of the weld metal. Thus, it should not be used to make quantitative comparisons of weld metals.

The transverse weld tensile test is most commonly used to qualify welding procedures to ensure that they yield welds that equal or exceed the design strength requirements. Only the ultimate tensile strength and the location of the fracture are normally reported when performing transverse weld tension tests.

Another type of transverse weld tension test is the tubular tension test. This test evaluates the strength of a complete girth weld in small-diameter (generally less than 3 in. [75 mm]) pipes by placing the welded pipe directly in the tension testing machine. As with other composite weldment tests, only the ultimate tensile strength is typically reported.

Fillet Weld Shear Test. The fillet weld shear test is employed using a universal test machine to determine the shear strength of fillet welds. The test specimens are usually intended to represent actual weldments, so the welds are prepared using production procedures. Figure 6.6 illustrates the two specimen types, longitudinal and transverse.

In the fillet weld shear test, specimen preparation procedures are crucial if consistent, accurate test results

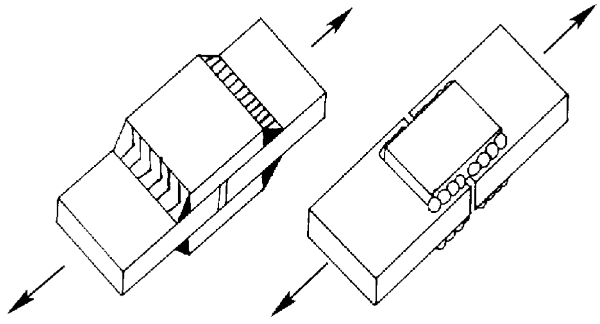
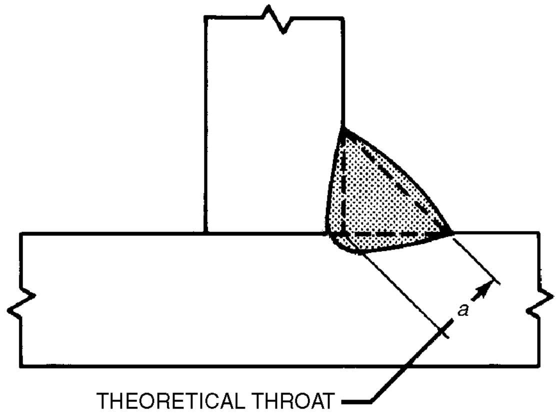


Figure 6.6—Longitudinal and Transverse Fillet Weld Specimens for Shear Stress Testing



$$\tau = \frac{P}{L \times a}$$

Key:
τ = Shear strength of the weld, psi (N/mm^2)
P = Load, lb (N)
L = Total length of the fillet weld sheared, in. (mm)
a = Theoretical throat dimension, in. (mm)

Figure 6.7—Method Used to Determine the Shear Strength of Fillet Welds

are to be obtained. For example, the stress concentration at the root of the transverse fillet weld increases with increasing root opening, and variations in root opening can cause inconsistent test results. Test specimens are also sensitive to heat-affected-zone cracking, undercut, and bead surface contour. For this reason, the longitudinal edges of transverse specimens should be machined to provide smooth surfaces, eliminating crater effects. Corners should also be rounded slightly.

The results normally reported for transverse and longitudinal shear tests are the shear strength of the weld metal and the location of the fracture. The shear strength is calculated by dividing the load by the shear area (effective weld length multiplied by the theoretical throat), as shown in Figure 6.7. Transverse shear specimens are tested as double lap joints to avoid rotation and bending stresses during testing.

The longitudinal shear test measures the shear strength of fillet welds when specimens are loaded parallel to the axis of the welds. To avoid bending during testing, two identical welded specimens are machined and then tack welded together, as indicated in Figure 6.8. Alternatively, the lap plates can be welded to a single set of base plates. Test results are calculated and reported as shown in the figure.

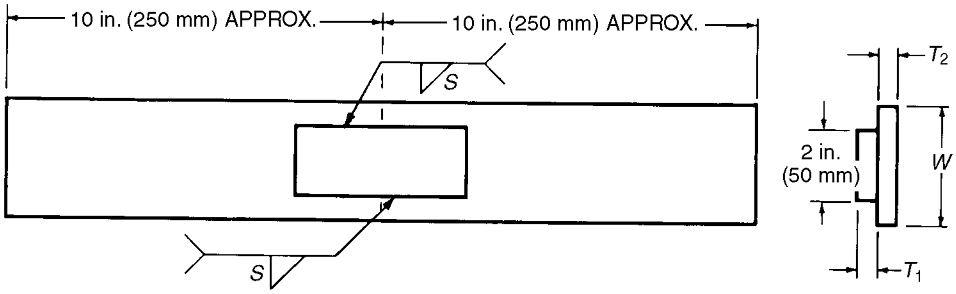
Tension-Shear Test for Brazed Joints. The tension-shear test is used on brazed joints to determine the strength of the filler metal. Figure 6.9 illustrates the specimen configuration and joint designs used for this test. Two single ferrous or nonferrous sheets 1/8 in. (3 mm) thick are joined by brazing with a filler metal. The shear strength of the filler metal is calculated by dividing the tensile load at failure by the brazed area. Such test specimens require suitable fixturing during brazing to maintain accurate specimen alignment.

Although the tension-shear test has been standardized for the control testing of samples from production brazing cycles, it is used primarily as a research tool for the development of filler metals and brazing procedures. It is also used to compare filler metals produced by various manufacturers.[15]

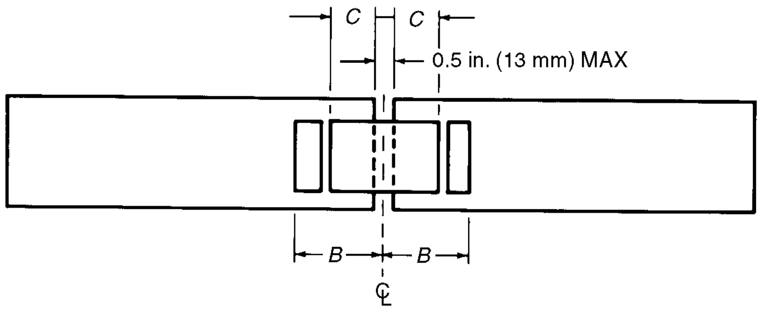
STRENGTH TESTS FOR RESISTANCE WELDS

Tension and tension-shear tests determine the strength of welds from specimens that can be pulled in a tension testing machine. These tests are used to determine the effect of weld parameter changes on resistance and seam welds. Test specimen dimensions, test fixtures, and statistical methods for evaluating resistance weld test results are specified in *Recommended Practices for Resistance Welding,* AWS C1.1M/C1.1.[16]

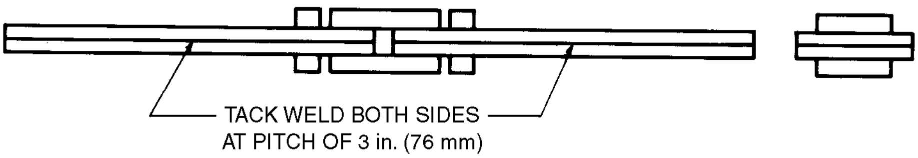
15. For additional information, consult American Welding Society (AWS) Committee on Brazing and Soldering, *Standard Methods for Evaluating the Strength of Brazed Joints in Shear,* ANSI/AWS C3.2, Miami: American Welding Society.
16. American Welding Society (AWS) Committee on Resistance Welding, *Recommended Practices for Resistance Welding,* AWS C1.1M/C1.1, Miami: American Welding Society.



(A) Step 1: Deposit Welds "S"



(B) Step 2: Machine Groove in Base Plate



(C) Step 3: Tack Two Pieces As Indicated

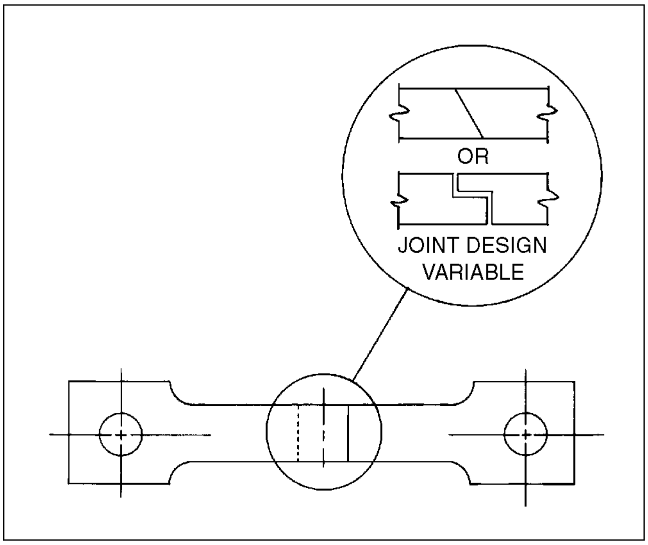
Key:
- $2B$ = Length of the lap piece, in. (mm)
- C = Length of weld tested, in. (mm)
- S = Specified size of the weld, in. (mm)
- T_1 = Thickness of the lap piece, in. (mm)
- T_2 = Thickness of the base plate, in. (mm)
- W = Width of the lap piece, in. (mm)

S	T_1	T_2	W	B	C
1/8	1/4	1/4	3		1-1/2
1/4	1/2	3/8	3		1-1/2
3/8	3/4	1/2	3		1-1/2
1/2	1	5/8	3-1/2*		1
ALL				2-1/4	

*For 7 in. (178.0 mm) on each end of the base plates, the 3-1/2 in. (89.0 mm) width may have to be reduced to 3 in. (76.0 mm) to accommodate the jaws of the test machine.

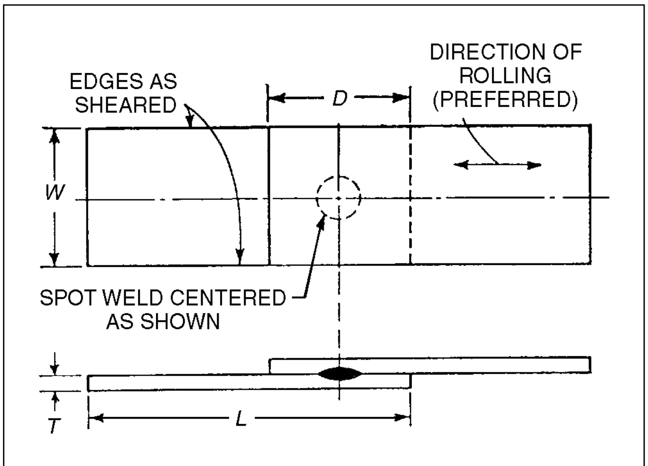
in.	mm	in.	mm
1/8	3.0	1-1/2	38.0
1/4	6.5	2	51.0
3/8	9.5	3	76.0
1/2	12.5	3-1/2	89.0
5/8	16.0	7	178.0
3/4	19.0	10	254.0
1	25.5		

Figure 6.8—Procedure for the Preparation of a Longitudinal Fillet Weld Specimen for a Shear Test



Source: American Welding Society (AWS) Committee on Brazing and Soldering, 1982, *Standard Methods for Evaluating the Strength of Brazed Joints in Shear*, ANSI/AWS C3.2-82R, Miami: American Welding Society, Figure 12.7.

Figure 6.9—AWS Standard Tension-Shear Test Specimen Used in the Testing of Brazed Joints



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 8.

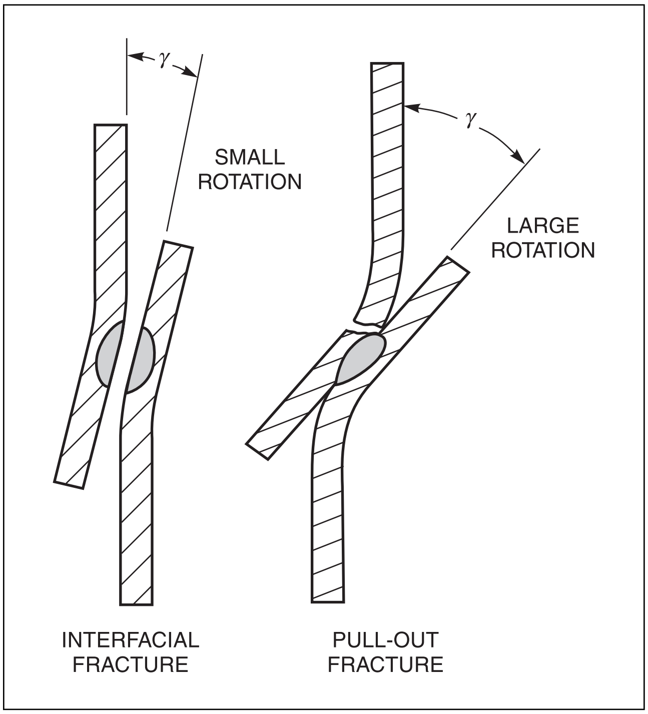
Figure 6.10—Tension-Shear Test Specimen

Tension-Shear Test

The tension-shear test for resistance welds is similar to the test used to evaluate the strength of arc welds. The spot weld test specimen depicted in Figure 6.10 is prepared by overlapping suitable-sized coupons and making a spot weld in the center of the overlapped area. A similar specimen can be prepared to test resistance seam welds. In this case, a transverse specimen is used; that is, the weld is placed across the width of the coupon. The specimen is then tested in a standard tension test machine.

As the sheet metal coupons are lapped, the tensile specimen generally bends and rotates, as illustrated in Figure 6.11. Failure generally occurs in the form of either an interfacial fracture or a pull-out fracture. Interfacial fractures, which occur because the bond between the two members is weaker than the base material, are generally undesirable. Pull-out fractures occur either because (1) the weld is stronger than the base metal, which results in significant rotation if the weldment is ductile, as shown in Figure 6.11, or (2) the base metal or the heat-affected zone is brittle.

The rotation within the sample may cause the spot weld to fail through or around the nugget. When the specimen thickness is 0.10 in. (2.6 mm) or greater, the wedge grips of the test machine should be offset to reduce the eccentric loading on the weld. Alternatively,



Source: American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 9.

Figure 6.11—Twisting Angle, γ, at Fracture in the Tension-Shear Test

metal pads can be applied to the ends of the specimens to eliminate the bending forces.

Easy and inexpensive, tension-shear tests are commonly used in the quality assurance testing of production welds. The ultimate strength of the specimen and the mode of failure, such as the shearing of the weld metal (interfacial fracture) or tearing of the base metal (pull-out fracture), and the type of fracture (ductile or brittle) are determined and reported. It may also be desirable to measure the bend angle between the weld interface and the tensile axis at fracture, as shown in Figure 6.11. The ductility of the weld is frequently reported by taking the ratio of the direct-tension load to the tension-shear load. Typical results are listed in Table 6.1.

Direct-Tension Test

The direct-tension spot weld test is used to measure the strength of welds for loads applied in a direction normal to the interface of the spot weld. Applicable to ferrous and nonferrous metals of all thicknesses, this test is employed to determine the relative notch sensitivity of spot welds. It is also used in the development of welding schedules and in researching the weldability of new alloys. It is important to note, however, that direct-tension testing is not normally used for the quality control of production welds.

Two types of specimens, the cross-tension and the U-specimen, are used in the performance of direct-tension testing. Cross-tension specimens, shown in Figure 6.12, can be used for all alloys and thicknesses. The specimen shown in Figure 6.12(A) is used when the thickness of the metal is under 0.19 in. (4.8 mm) because the specimen must be reinforced to prevent excessive bending. For thicker specimens like those shown in Figure 6.12(B), the holes may be eliminated.

Table 6.1
Ratio of Direct-Tension to Tension-Shear Specimen Loads

Material	Typical Ratio Range
Low-carbon steel	0.60 to 0.99
Medium-carbon steel (0.2 C)	0.18 to 0.21
Low-alloy, high-strength steel	0.21 to 0.28
Austenitic stainless steel	0.55 to 0.82
Ferritic stainless steel	0.25 to 0.33
Aluminum base	0.37 to 0.43
Nickel base	0.71 to 0.81
Titanium base	0.27 to 0.52

The test fixture depicted schematically in Figure 6.13 is used to provide additional support for specimens up to 0.19 in. (4.8 mm) thick. This fixture is utilized with a standard tensile testing machine. The fixture illustrated in Figure 6.14 is used for specimens 0.19 in. thick and greater. Depending on the orientation of the specimen, either compression [Figure 6.14(A)] or tension [Figure 6.14(B)] may be used to apply tension to the spot weld.

The U-specimen, shown in Figure 6.15, is the other type of specimen used in direct-tension testing. To form a test specimen, two U-channels are spot welded back to back. The specimens are then pinned to filler blocks with pull-tabs. A tensile load is applied to the spot weld through the pin connections. Finally, the maximum load that causes the weld to fail is measured and recorded. The weld fails by either pulling a plug (tearing around the edge of the spot weld) or by pulling apart across the weld metal (tensile failure).

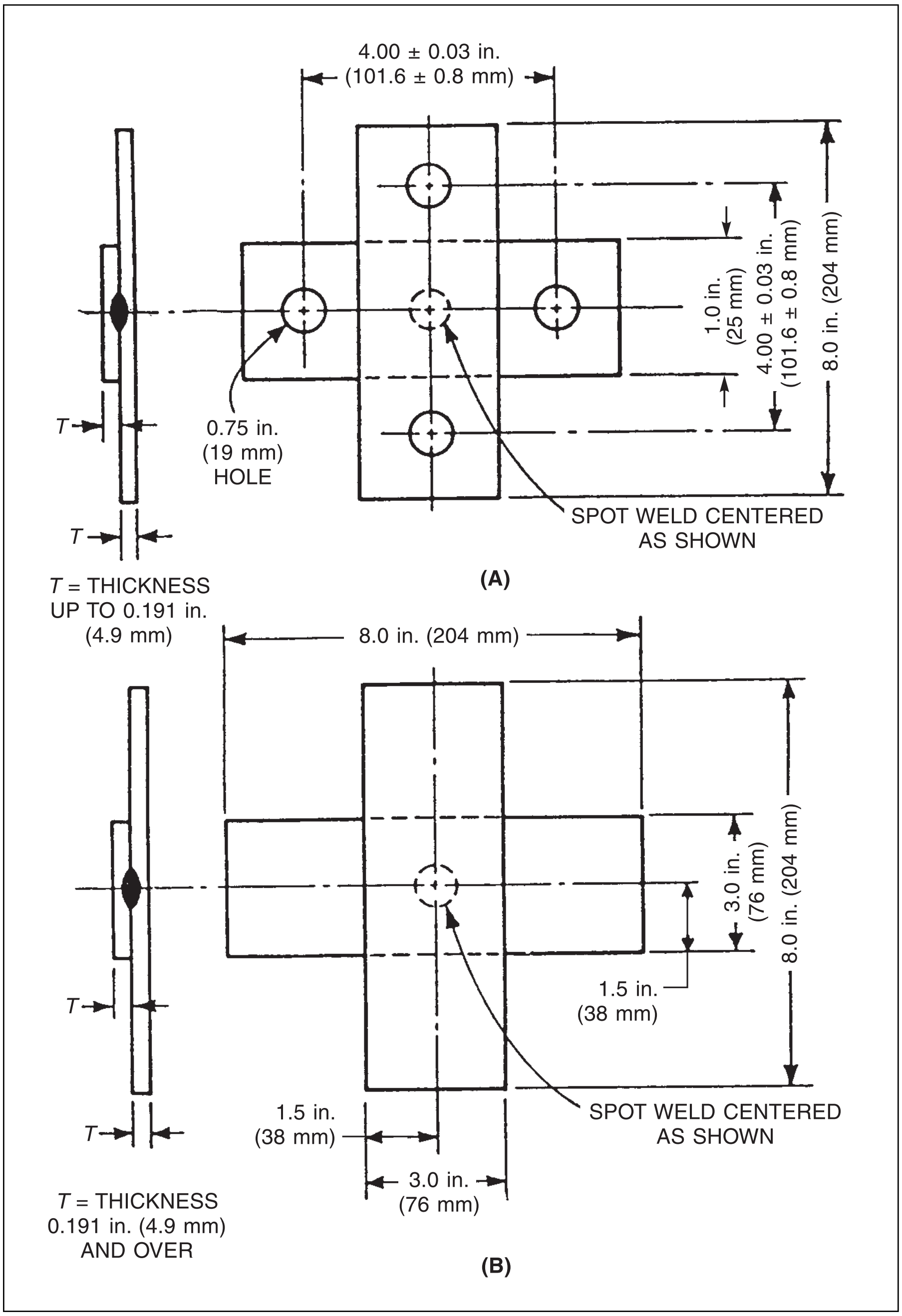
The direct-tension load is normally lower than the tension-shear load for the same weld size and base alloy. The ratio of the direct-tension load to the tension-shear load is frequently referred to as the *ductility* of the weld, which is a measure of the notch sensitivity of the weld. A ratio greater than 0.5 is considered ductile. Table 6.1, presented above, lists typical ratio ranges for spot welds in several base metals. Ratios less than 0.30 indicate notch-sensitive welds.

Peel Test

The peel test, depicted in Figure 6.16, is a simple variation of the direct-tension test. It is commonly used as a production control test. In this test, the size of the weld button is measured, and the weld fracture mode is determined. The production welds are acceptable if the measured weld button size is equal to or greater than the standard weld size as determined by tension-shear and direct-tension tests.

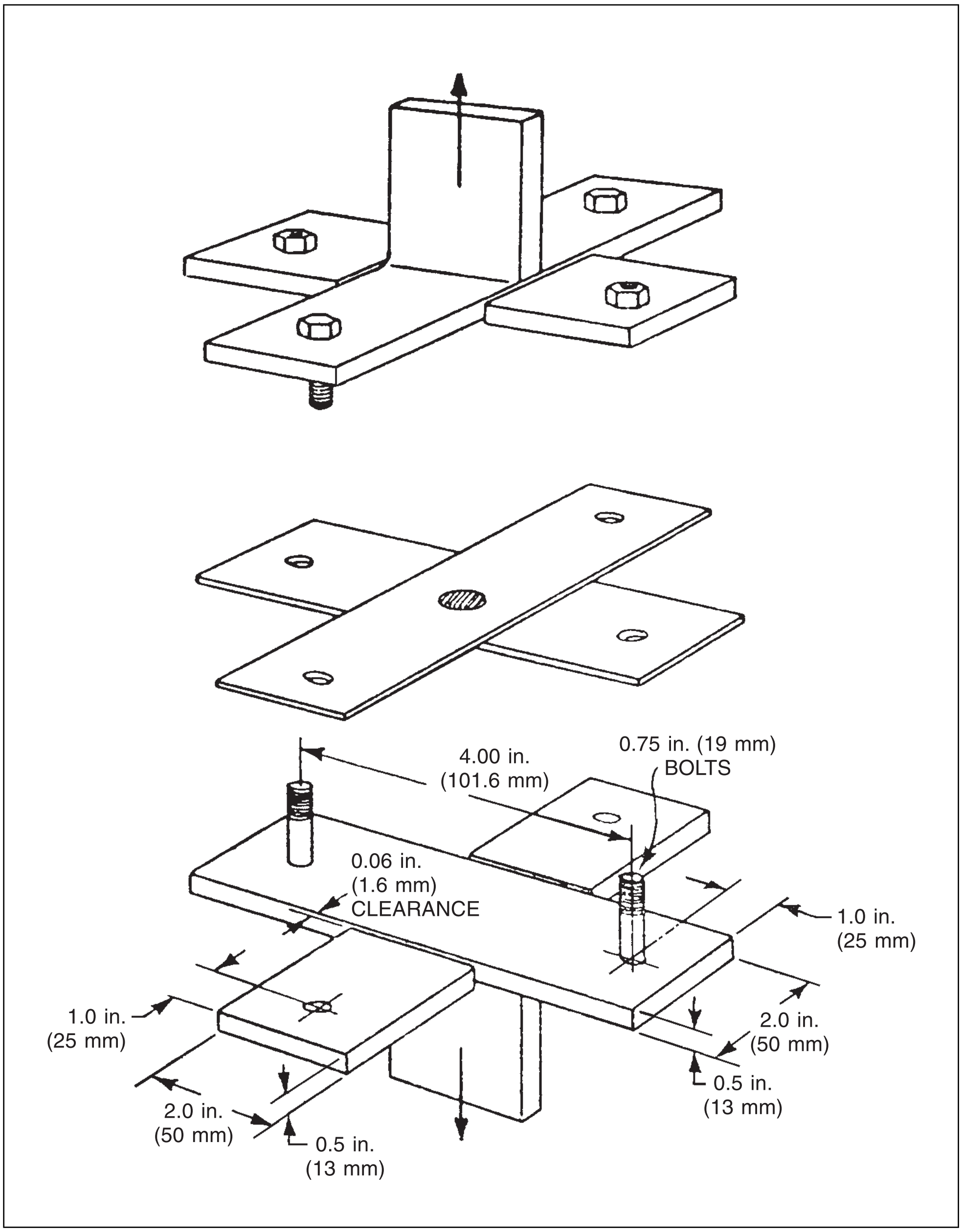
Although this test is rapid and inexpensive, it may not be suitable for high-strength base metals or thicker sheets. If this is the most important production test, it is advisable to consider that the results may be influenced significantly by the speed and direction of the pulling force. The successful pulling of a weld button may not be a significant indicator of ductility or notch sensitivity. It is possible that a button may be pulled with a slow tearing motion, whereas a quick tug would result in interfacial fracture. The publication *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1,[17] should be consulted for specimen dimensions.

17. See Reference 16.



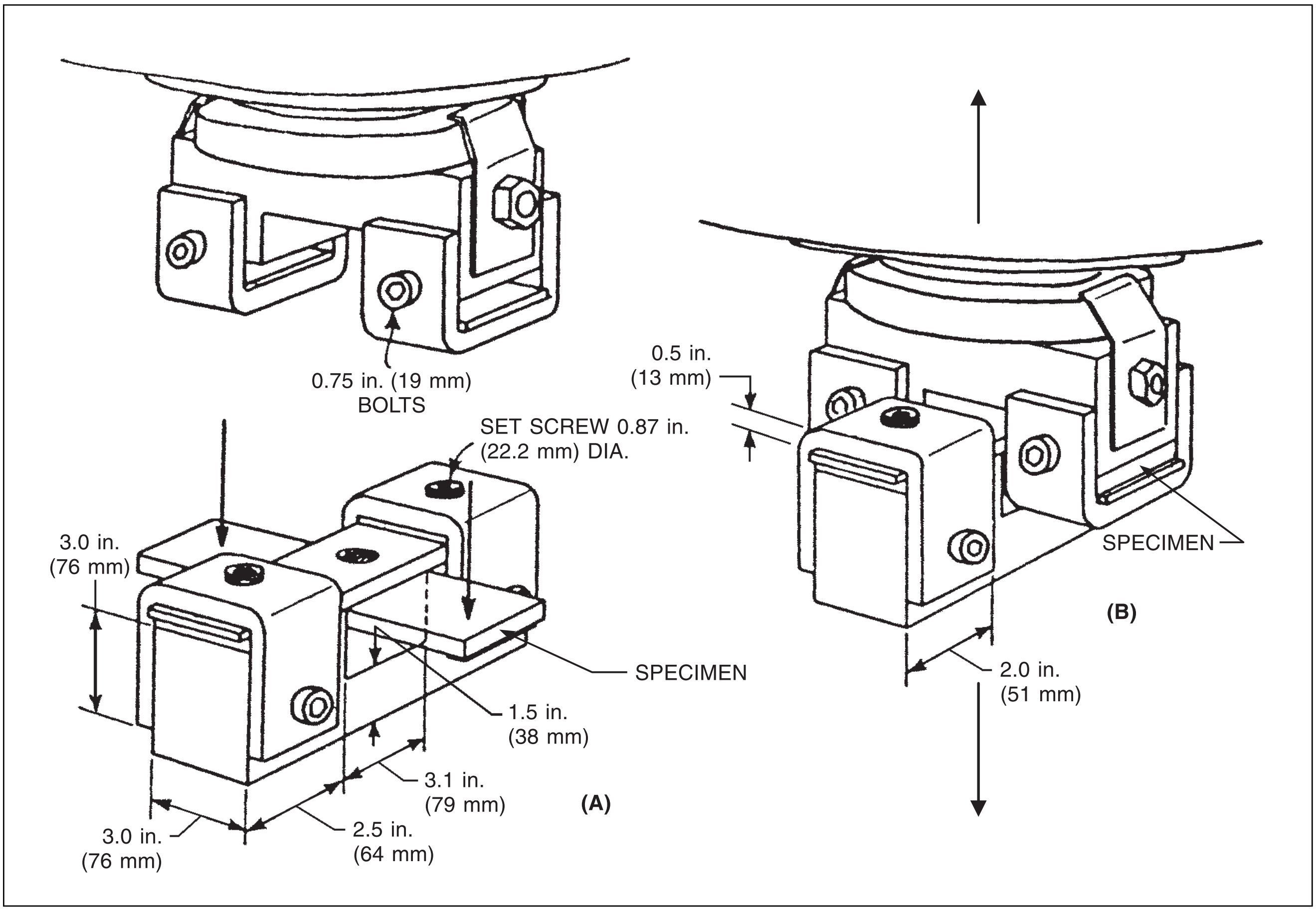
Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 10.

Figure 6.12—Cross-Tension Test Specimens: (A) Thin and (B) Thick



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 11.

Figure 6.13—Fixture Employed in Cross-Tension Testing for Thicknesses up to 0.19 in. (4.8 mm)



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 12.

Figure 6.14—Fixture Employed in Cross-Tension Testing for Thicknesses of 0.19 in. (4.8 mm) and Over: (A) Compression Loading and (B) Tension Loading

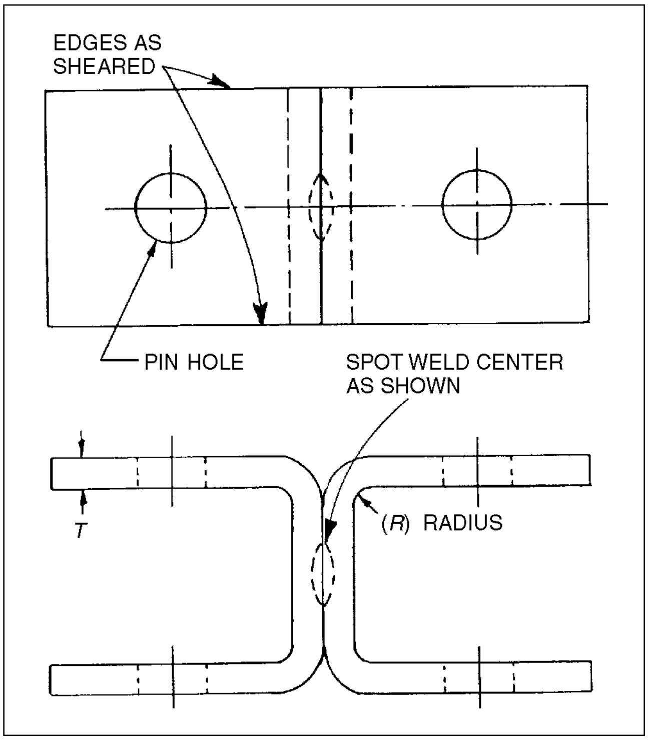
Torsion-Shear Test

A torsion-shear test may be used to evaluate spot welds where a measure of strength and ductility are required. This test can be performed as a simple production test with little or no equipment. It can also be used as a laboratory test. A typical coupon and fixture for this test are shown in Figure 6.17.

In this case, torsional shear is applied on the weld of a square test specimen by placing the specimen between two recessed plates. The upper plate is held rigid by a hinge while the lower plate is fastened to a rotating disk. After the specimen is placed in the square recess of the lower plate, the upper plate is closed over it and locked into position. Torque is applied by means of a rack and pinion attached to the disk. It is important that the two halves of the specimen be engaged separately by the two plates and that the weld be centrally located with respect to the axis of rotation. Values for the ultimate torque can be calculated by multiplying the length of the moment arm by the maximum load required to twist the sample to destruction.

A simplified qualitative variation of this method is presented in *Structural Welding Code—Sheet Steel,* ANSI/AWS D1.3.[18] A spot weld is made between a sheet steel and a base plate, and the sheet is hammered sideways until the welds fails. The acceptance criteria are limited to the presence of full fusion and the absence of weld defects.

18. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Sheet Steel,* ANSI/AWS D1.3, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 13.

Figure 6.15—Direct-Tension U-Test Specimen

Pillow Test for Continuous Resistance Seam Welds

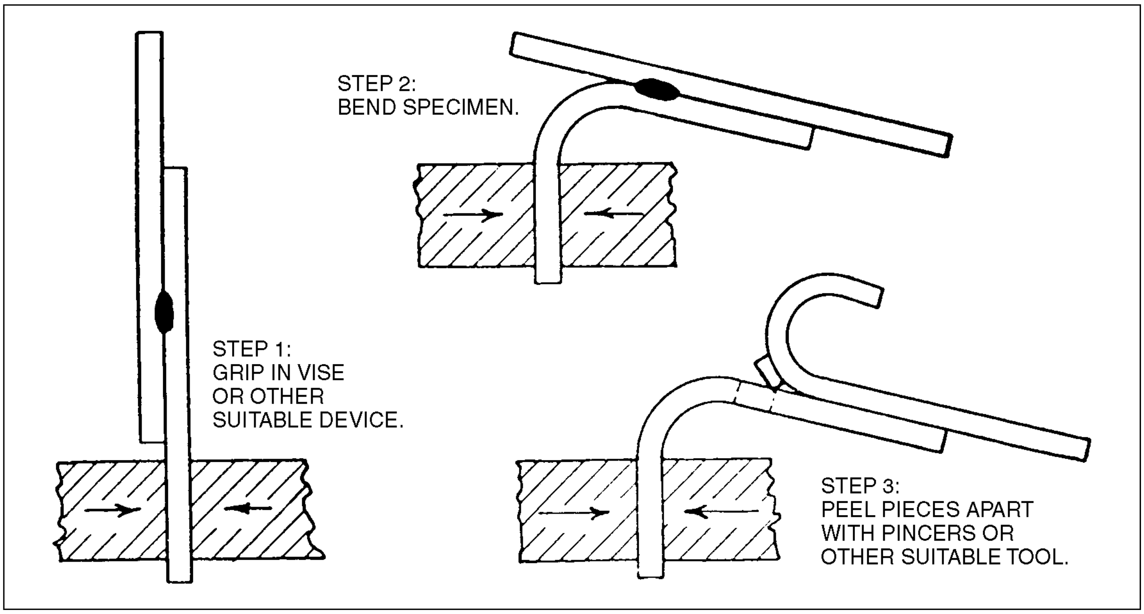
The pillow test is used in seam welding applications to simulate the service conditions of the welded leak-tight joint. The test configuration is shown in Figure 6.18. One of the two flat plates is fitted with a pressure connection. The two plates are then joined with a continuous seam weld around the outside edge. The specimen is then pressurized (e.g., with hydraulic fluid).

Evaluation of the test includes examining the specimen for leakage or base metal failure at the proof pressure. It may be necessary to contain the specimen between two plates during the test to restrict its deformation and balance the stress along the weld seam.

Additional Resistance Weld Tests

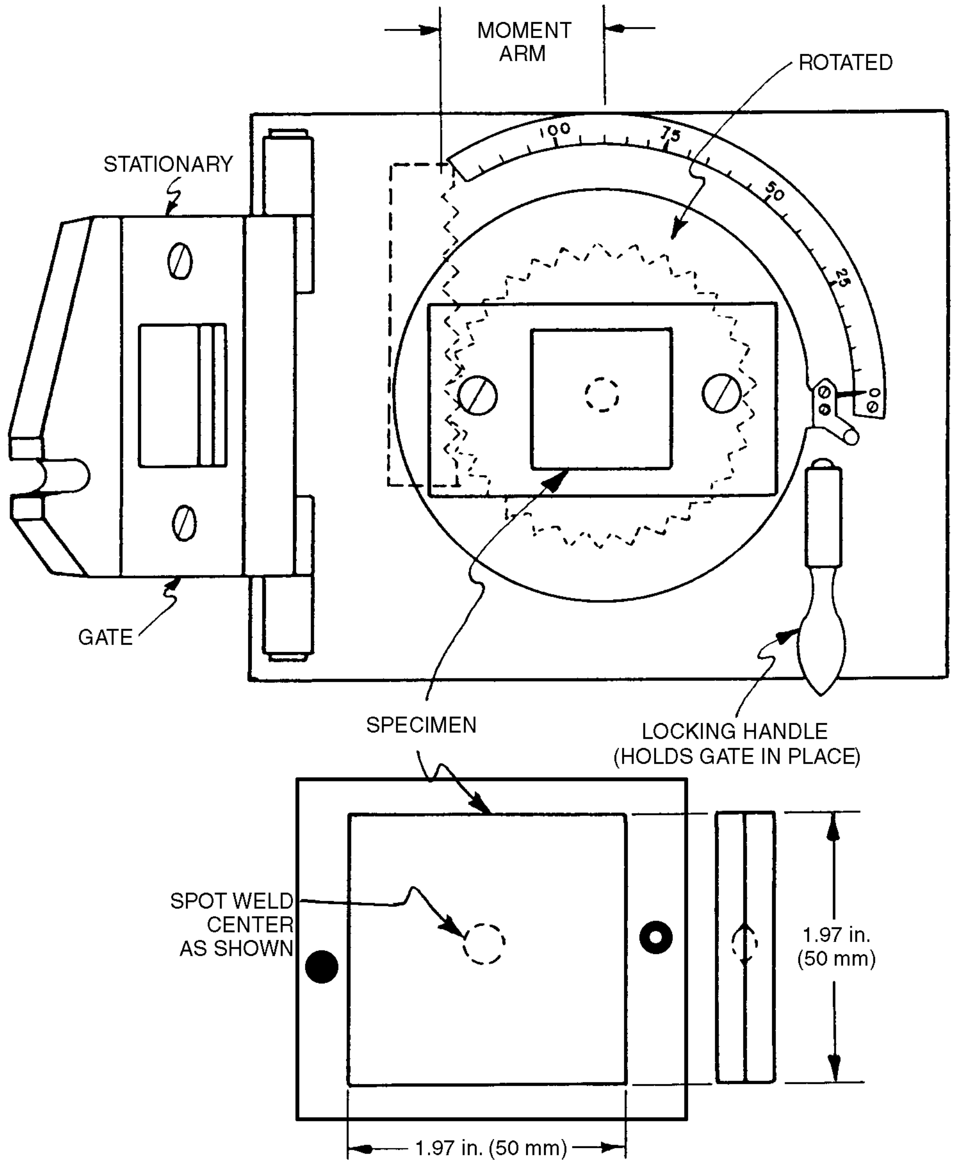
A number of variations of the tests discussed above are described in *Recommended Practices for Resistance Welding*, AWS C1.1M/C.1.[19] This publication provides information on these test variations as well as on the pull test, various impact tests, and fatigue testing.

19. See Reference 16.



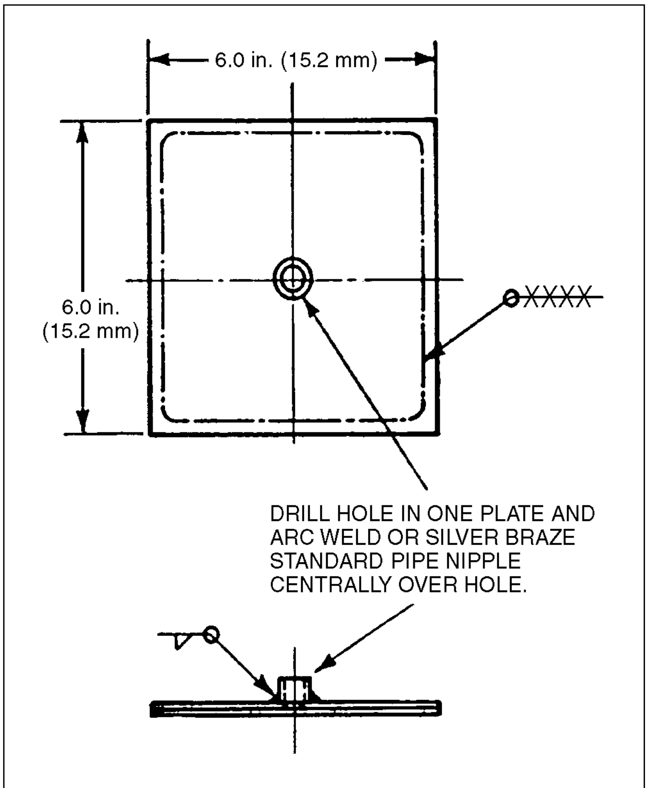
Source: American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 3.

Figure 6.16—Peel Test Procedure



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 16.

Figure 6.17—Test Specimen and Typical Equipment for the Torsion-Shear Test



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, Recommended Practices for Resistance Welding, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 22.

Figure 6.18—Pillow Test for Seam Welds

HARDNESS TESTS

Hardness tests determine the resistance of a material to penetration. Nonetheless, hardness test results are often used as a quick method of approximating ultimate tensile strength in the local area tested. Hardness measurements can also provide information about metallurgical changes caused by welding. In alloy steels, a high hardness could indicate the presence of martensite in the weld's heat-affected zone, while a low hardness may indicate an overtempered condition. Welding can cause significantly lower hardness in the heat-affected zone of cold-worked metal because of recovery and recrystallization. In age-hardened metal, welding can result in a lower heat-affected-zone hardness because of overaging.

Hardness tests are performed using a penetrator that is forced against the surface of the test specimen to form an indentation. The type of material, the geometry, and the size of the penetrator depend on the test method and hardness range and include hardened-steel spheres and diamond pyramids. Hardness test methods for metals include the Brinell, Knoop, Vickers, and Rockwell tests. The first three tests utilize the area of indentation under load as the measure of hardness. The Rockwell test uses the depth of indentation under load as a hardness measure. The diameter or depth of the indentation is then measured and converted to a hardness number using a standardized procedure for each method as defined in *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A 370.[20] The hardness number must always be reported along with the method, test load, and type and size of penetrator used, either explicitly or using standard abbreviations such as those defined in the document cited above.

The selection of a hardness test method depends primarily on the hardness or strength of the metal, the size of the welded joint, and the type of information desired. Hardness tests measure the average hardness of the material under the indentation. Tests that make larger indentations are more representative of the bulk properties of a metal. The Brinell test produces a large indentation, typically 0.08 in. to 0.22 in. (2 mm to 5.6 mm) in diameter, yielding an average hardness for the largest sample of metal. The Rockwell test produces a much smaller indentation, which is suited to hardness traverses. However, these indentations are still macroscopic and may be larger than the precise areas of interest, such as a fusion zone or a coarse-grain region in the heat-affected zone.

For microscopic areas, the Vickers and Knoop microhardness tests make small indentations that are well suited for hardness measurements of the various regions of the heat-affected zone and for closely spaced traverses. These tests, which are used with a metallograph, can measure the hardness of individual grains and inclusions in the metal.

Hardness tests can be performed on ground, polished, and polished-and-etched cross sections of a weld joint. Measurements can be made on any specific area of the weld or base metal, depending on the test method and purpose. Frequently, hardness indentations are made at regular intervals across an entire weld cross section, as shown in Figure 6.19. Hardness traverses of a weld cross section are often performed using the Vickers method because the very small indentation provides information on local microstructural changes in the weld metal and heat-affected zone.

An approximate interrelationship exists among the results of the different hardness tests and the tensile strength of some metals. For example, the approximate ultimate tensile strength of carbon and low-alloy steel

20. See Reference 8.

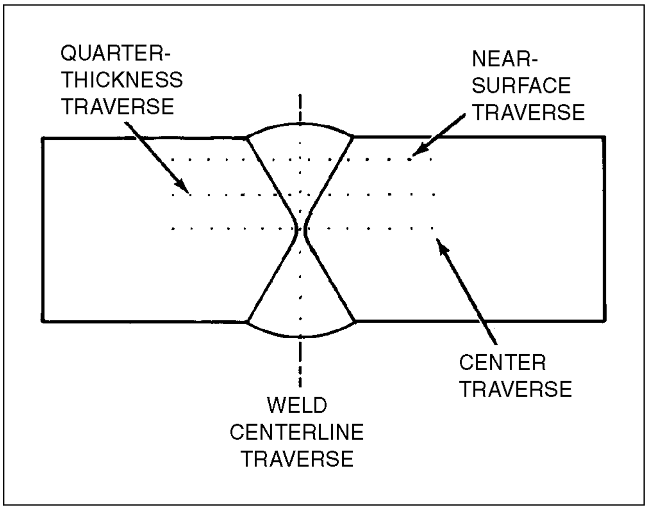


Figure 6.19—Typical Hardness Traverses for Double-V Groove Welded Joints

in ksi (MPa) is approximately one half (3-1/3) the Brinell hardness number. Table 6.2 provides the relationship for nonaustenitic steels, while Table 6.3 provides hardness conversions for austenitic steels. These correlations should be used with caution when applied to welded joints or any metal with a heterogeneous structure.

In hardness testing, proper specimen preparation is important for reliable results. The surface should be flat and reasonably free of scratches. In addition, it must be perpendicular to the applied load for uniform indentations. With thin, soft metals, the testing machine must produce a shallow indentation that is not restricted by the anvil of the testing machine. This can be accomplished (particularly with a Rockwell testing machine) with a small indenter and a light load.

BRINELL HARDNESS TEST

The Brinell hardness test consists of impressing a hardened steel ball into the test surface using a specified load for a definite time. Following this, the diameter of the impression is accurately measured and converted to a hardness number from a table. Examination should be performed according to the requirements of *Standard Test Method for Brinell Hardness of Metallic Metals,* ASTM E 10.[21] Stationary machines impress a ball 0.4 in. (10 mm) in diameter into the test object. The load for steel is 6600 pound-force (lbf) (3000 kilograms [kg]), whereas it is 1100 lbf or 3300 lbf (500 kg or 1500 kg) for softer metals. Two measurements of the impression diameters are taken at 90° from one another using a special Brinell microscope. The mean diameter is used to determine the Brinell hardness from the table.

To test larger components, portable Brinell equipment consisting of a 0.3 in. or 0.4 in. (7 mm or 10 mm) ball and a calibrated reference bar is available. A hammer blow is used to indent simultaneously both the indenter bar and the material being tested. The hardness of the material being tested can be measured using a special slide rule or inserting the hardness of the reference bar and the diameters of the two indentations into a formula. The accuracy of this method is enhanced by selecting a reference bar of approximately the same hardness as the unknown test material.

ROCKWELL HARDNESS TEST

The Rockwell hardness test measures the depth of residual penetration made by a small hardened steel ball or diamond cone. The test is performed by applying a minor load of 22 lbf (10 kg) to seat the penetrator in the surface of the specimen and hold it in position. The machine dial is turned to a set point, and a major load is applied. After the pointer comes to a rest, the major load is released, while the minor load remains.

The Rockwell hardness number is read directly on the dial. Hardened steel balls 1/8 in. or 1/16 in. (3.2 mm or 1.6 mm) in diameter are used for soft metals, whereas a cone-shaped diamond penetrator is used for hard metals. Testing is conducted in accordance with *Standard Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials,* ASTM E 18.[22]

MICROHARDNESS TESTS

The Knoop and Vickers microhardness tests determine the hardness of a very small area that is on the order of a few grains wide. The polished sample is viewed under a microscope at magnifications up to 800X. In these tests, the area of interest is located under the microscope, and the turret is then rotated to bring the indenter over the area. A calibrated machine is used to force a diamond indenter with a specified geometry into the sample using test loads of 1 gram-force (gf) to 100 gf. The turret is rotated back, and the diagonal of

21. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Method for Brinell Hardness of Metallic Materials,* ASTM E 10, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

22. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials,* ASTM E 18, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

Table 6.2
Approximate Hardness Conversion Numbers for Nonaustenitic Steels

Rockwell B Scale, 100 kgf Load, 1/16 in. (1.588 mm) Ball	Vickers Hardness Number	Brinell Indentation Diameter	Brinell Hardness, 3000 kgf Load, 10 mm Ball	Knoop Hardness, 500 kgf Load and Over	Rockwell A Scale, 60 kgf Load 1/16 in. Ball	Rockwell F Scale, 60 kgf Load, 1/16 in. Ball	Rockwell Superficial Hardness			Approximate Tensile Strength, ksi (MPa)
							15T Scale, 15 kgf Load, 1/16 in. Ball	30T Scale, 30 kgf Load, 1/16 in. Ball	45T Scale, 30 kgf Load, 1/16 in. Ball	
100	240	3.91	240	251	61.5	—	93.1	83.1	72.9	116 (800)
99	234	3.96	234	246	60.9	—	92.8	82.5	71.9	114 (785)
98	228	4.01	228	241	60.2	—	92.5	81.8	70.9	109 (750)
97	222	4.06	222	236	59.5	—	92.1	81.1	69.9	104 (715)
96	216	4.11	216	231	58.9	—	91.8	80.4	68.9	102 (705)
95	210	4.17	210	226	58.3	—	91.5	79.8	67.9	100 (690)
94	205	4.21	205	221	57.6	—	91.2	79.1	66.9	98 (675)
93	200	4.26	200	216	57.0	—	90.8	78.4	65.9	94 (650)
92	195	4.32	195	211	56.4	—	90.5	77.8	64.8	92 (635)
91	190	4.37	190	206	55.8	—	90.2	77.1	63.8	90 (620)
90	185	4.43	185	201	55.2	—	89.9	76.4	62.8	89 (615)
89	180	4.48	180	196	54.6	—	89.5	75.8	61.8	88 (605)
88	176	4.53	176	192	54.0	—	89.2	75.1	60.8	86 (590)
87	172	4.58	172	188	53.4	—	88.9	74.4	59.8	84 (580)
86	169	4.62	169	184	52.8	—	88.6	73.8	58.8	83 (570)
85	165	4.67	165	180	52.3	—	88.2	73.1	57.8	82 (565)
84	162	4.71	162	176	51.7	—	87.9	72.4	56.8	81 (560)
83	159	4.75	159	173	51.1	—	87.6	71.8	55.8	80 (550)
82	156	4.79	156	170	50.6	—	87.3	71.1	54.8	77 (530)
81	153	4.84	153	167	50.0	—	86.9	70.4	53.8	73 (495)
80	150	4.88	150	164	49.5	—	86.6	69.7	52.8	72 (495)
79	147	4.93	147	161	48.9	—	86.3	69.1	51.8	70 (485)
78	144	4.98	144	158	48.4	—	86.0	68.4	50.8	69 (475)
77	141	5.02	141	155	47.9	—	85.6	67.7	49.8	68 (470)
76	139	5.06	139	152	47.3	—	85.3	67.1	48.8	67 (460)
75	137	5.10	137	150	46.8	99.6	85.0	66.4	47.8	66 (455)
74	135	5.13	135	147	46.3	99.1	84.7	65.7	46.8	65 (450)
73	132	5.18	132	145	45.8	98.5	84.3	65.1	45.8	64 (440)
72	130	5.22	130	143	45.3	98.0	84.0	64.4	44.8	63 (435)
71	127	5.27	127	141	44.8	97.4	83.7	63.7	43.8	62 (425)
70	125	5.32	125	139	44.3	96.8	83.4	62.1	42.8	61 (420)
69	123	5.36	123	137	43.8	96.2	83.0	62.4	41.8	60 (415)
68	121	5.40		135	43.3	95.6	82.7	61.7	40.8	59 (405)
67	119	5.44		133	42.8	95.1	82.4	61.0	39.8	58 (400)
66	117	5.48		131	42.3	94.5	82.1	60.4	38.7	57 (395)
65	116	5.51		129	41.8	93.9	81.8	59.7	37.7	56 (385)
64	114	5.54		127	41.4	93.4	81.4	59.0	36.7	—
63	112	5.58		125	40.9	92.8	81.1	58.4	35.7	—

Source: Adapted from American Society for Testing and Materials (ASTM) Subcommittee A01.13, 1997, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A 370-97a, West Conshohocken, Pennsylvania: American Society for Testing and Materials, Table 2B.

Table 6.3
Approximate Hardness Conversion Numbers for Austenitic Steels

Rockwell C Scale, 150 kgf Load, Diamond Penetrator	Rockwell A Scale, 60 kgf Load, Diamond Penetrator	Rockwell Superficial Hardness		
		15N Scale, 15 kgf Load, Diamond Penetrator	30N Scale, 30 kgf Load, Diamond Penetrator	45N, 45 kgf Load, Diamond Penetrator
48	74.4	84.1	66.2	52.1
47	73.9	83.6	65.3	50.9
46	73.4	83.1	64.5	49.8
45	72.9	82.6	63.6	48.7
44	72.4	82.1	62.7	47.5
43	71.9	81.6	61.8	46.4
42	71.4	81.0	61.0	45.2
41	70.9	80.5	60.1	44.1
40	70.4	80.0	59.2	43.0
39	69.9	79.5	58.4	41.8
38	69.3	79.0	57.5	40.7
37	68.8	78.5	56.6	39.6
36	68.3	78.0	55.7	38.4
35	67.8	77.5	54.9	37.3
34	67.3	77.0	54.0	36.1
33	66.8	76.5	53.1	35.0
32	66.3	75.9	52.3	33.9
31	65.8	75.4	51.4	32.7
30	65.3	74.9	50.5	31.6
29	64.8	74.4	49.6	30.4
28	64.3	73.9	48.8	29.3
27	63.8	73.4	47.9	28.2
26	63.3	72.9	47.0	27.0
25	62.8	72.4	46.2	25.9
24	62.3	71.9	45.3	24.8
23	61.8	71.3	44.4	23.6
22	61.3	70.8	43.5	22.5
21	60.8	70.3	42.7	21.3
20	60.3	69.8	41.8	20.2

Source: Adapted from American Society for Testing and Materials (ASTM) Subcommittee A01.13, 1997, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A 370-97a, West Conshohocken, Pennsylvania: American Society for Testing and Materials, Table 2C.

the resulting impression is then measured and converted into a hardness number. Both the Knoop and Vickers numbers are obtained by dividing the load used to produce the indentation (in gf and kilogram-force [kgf], respectively) by the resulting area of the indentation in square millimeters.

The Knoop indenter is a rhombic-based diamond pyramid. The 172° 30′ and 130° angles produce an indentation that is significantly longer than it is wide. The long axis is measured through the microscope, recorded, and converted to a hardness number.

The Vickers microhardness indenter is a square-based diamond pyramid with equal face angles of 136°. Both diagonals of the indentation are measured. The results are then averaged and converted to a hardness number.

Both Knoop testing and Vickers testing are performed in accordance with *Standard Test Method for Microindentation Hardness of Materials*, ASTM E 384.[23]

23. American Society for Testing and Materials (ASTM) Subcommittee E04.05, *Standard Test Method for Microindentation Hardness of Materials*. ASTM E 384, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

BEND TESTS

Bend tests provide a means to evaluate both the ductility and the soundness of welded joints. These tests are performed by bending a strip of the weldment to a specified radius. The outer surface of the bend specimen is subjected to extensive plastic yielding in tension, which can cause fractures or fissuring in less ductile material or open existing weld defects such as porosity and lack of fusion. Thus, when weld defects or hard, brittle zones are present, bend test specimens consistently fail.

Test specimens can be bent in a tension test machine (free bend) or wrapped around a mandrel of a specified diameter (guided bend). Most codes require guided bends but provide for the use of alternative test equipment, such as the bottom-ejecting guided bend test fixture, roller-equipped guided bend fixture, and the wraparound bend test fixture.

Figure 6.20 illustrates two guided bend test fixtures. Figure 6.20(A) is a bottom-ejecting plunger type fixture that can be used with a tension testing machine or jack. Figure 6.20(B) is a wraparound fixture that is typically a self-powered unit. The specific dimensional requirements for these fixtures (e.g., radius *A*) are defined by codes to provide a specified outer fiber tensile strain. This may vary with the material, but it is often 20%.

The guided bend test is most commonly used in welding procedure and welder performance qualification. The required specimen dimensions are specified in the relevant code. For weld procedure qualification testing, the full weldment thickness is generally tested as a single specimen or split into multiple specimens when the thickness exceeds 1-1/2 in. (38 mm) or the width of the mandrel.

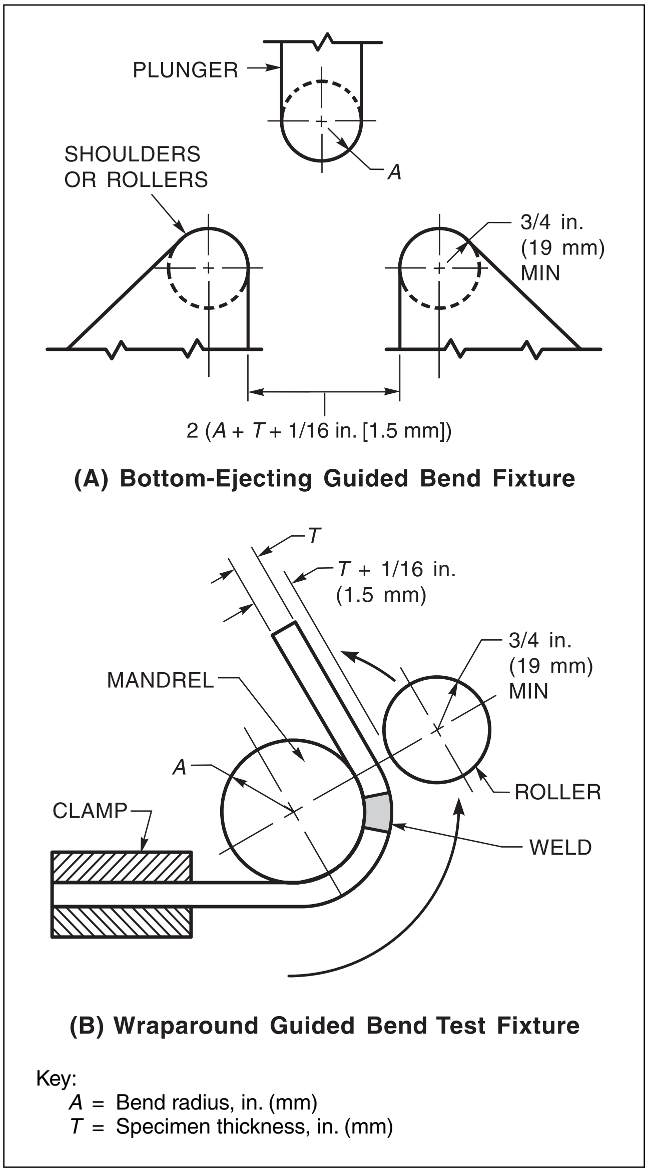
In qualification testing, the specimen thickness and bend radius are chosen according to the ductility of the metal being tested. Sound mild steel welds can easily achieve an outside fiber elongation of 20%. The strain on the outside fiber of the bend specimen can be approximated from the following formula:

$$\varepsilon = \frac{100T}{(2A + T)} \tag{6.1}$$

where

ε = Outer fiber strain, %;
T = Bend test specimen thickness, in. (mm); and
A = Inside bend radius, in. (mm).

Guided bend specimens may be longitudinal or transverse to the weld axis. Longitudinal bend tests are generally used to evaluate joints in dissimilar metals. In this test, the zones of the welded joint (weld metal, heat-affected zone, and base metal) are strained equally and simultaneously. This may be necessary to minimize nonuniform bending caused by nonuniform properties along the length of the bend test specimen. However, in the longitudinal test, weld flaws oriented parallel to the weld axis—incomplete fusion, inadequate joint penetration, or undercut, for example—are only moderately strained and may not cause failure.



Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 1998, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0, Miami: American Welding Society, Figure A1 and Figure A3.

Figure 6.20—Schematic Illustration of Typical Guided Bend Test Fixtures

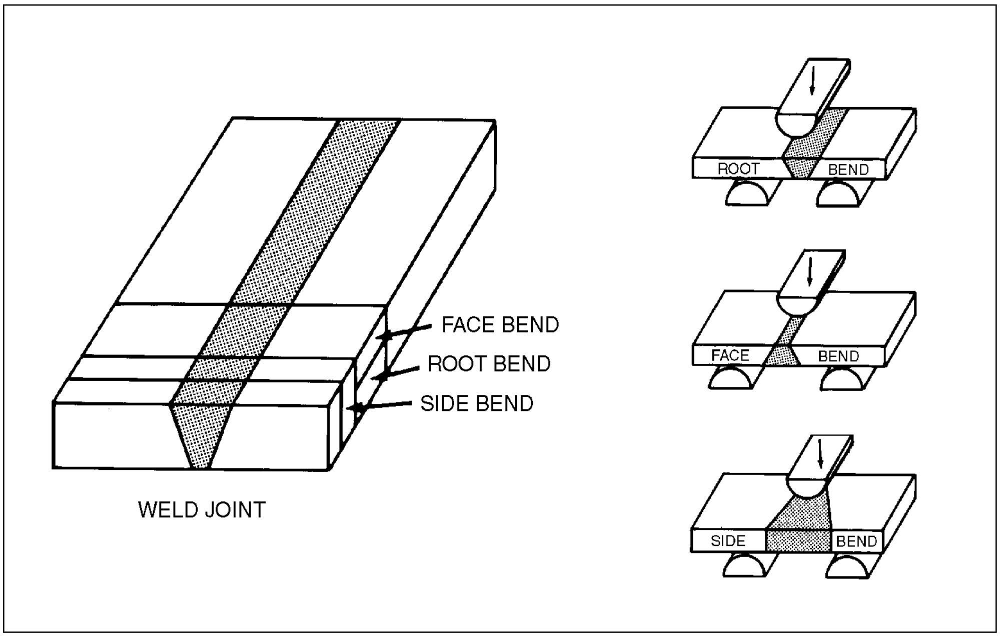


Figure 6.21—Specimen and Test Orientation of the Guided Bend Test

Transverse bend tests may be either face, root, or side tests, depending on the area that is in tension during the test, as shown in Figure 6.21. Face bend tests are performed with the weld face in tension. Root bend tests are performed with the weld root in tension, and side bends can be bent toward either side. Side bends are typically used when bend testing plates thicker than 3/8 in. (10 mm) to 3/4 in. (19 mm). Side bend tests strain the entire cross section of the weld. Thus, they are especially useful for exposing discontinuities that may not contribute to failure in face or root bend tests because of their location near the midthickness.

Transverse bend tests are particularly sensitive to the relative strengths of the weld metal, heat-affected zone, and base metal. An overmatching weld metal may prevent the weld zone from conforming exactly to the mandrel radius because the base metal deforms into a smaller radius. On the other hand, with undermatching weld strength, the specimen may bend in the weld to a radius smaller than that of the bending plunger or mandrel. In this case, failure may result because the ductility of the weld metal is exceeded, not because the weld metal contains a defect. Thus, in weldments with significant weld strength mismatch, longitudinal bend specimens should be used, although the use of a wraparound test fixture minimizes this effect.

FRACTURE TOUGHNESS TESTING

Fracture toughness test results provide data for use in fracture mechanics analyses to relate stress and crack size or to characterize the ductile-to-brittle transition temperature. Toughness tests are also used for purposes of production quality control.

The term *fracture toughness* refers to a material's resistance to the extension of a crack.[24] Crack propagation requires an energy source. In service, the stored elastic strain energy in the structure is the driving force for crack propagation. In fracture toughness tests, the testing machine produces the energy. The stored elastic strain energy of a stressed member, or energy per unit volume, is a product of its stress and strain. Thus, high-strength materials can store more elastic strain than low-strength materials when both are loaded to the same fraction of yield strength. Fracture mechanics

24. Refer to American Society for Testing and Materials (ASTM) Subcommittee E08.02, *Standard Terminology Relative to Fatigue and Fracture Testing*, ASTM E 1823, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

therefore indicates that greater toughness is needed in the high-strength material to avoid unstable fracture from identical cracks in the two materials.

Toughness tests can be grouped into three categories based on their use: crack propagation resistance, nil-ductility transition (NDT) temperature evaluation, and quality control. Fracture mechanics analyses are typically performed to determine the conditions under which a stationary crack will propagate or a running crack will arrest and require toughness measures that characterize the corresponding property (e.g., K_{IC}, drop weight test (DWT) no-break temperature).

Fracture toughness testing methods are described following a discussion of the fundamentals of fracture mechanics.

FUNDAMENTALS

Linear-elastic fracture mechanics (LEFM), elastic-plastic fracture mechanics (EPFM), and most other classical fracture mechanics analyses of cracks are based on crack propagation resistance. These methods predict the stress level at which a crack of a known size and shape will begin unstable propagation or stable tearing in a material of known toughness. The measure of toughness used in these analyses is plane-strain fracture toughness (K_{Ic}), which is applicable to the more brittle materials that exhibit little plasticity before unstable crack propagation. Elastic-plastic fracture mechanics is employed when significant yielding occurs before fracture. EPFM analyses require toughness measures such as J and crack tip opening displacement (CTOD or δ).[25]

These fracture toughness measures are determined from static tests that are performed at slow strain rates. Specimens are already cracked (e.g., by fatigue or an intentionally produced embrittled zone) before the testing begins. The load is increased while the crack opening is monitored. The maximum load, which can occur either during stable (slow) crack extension or at the point when unstable crack propagation occurs, is recorded. A significant unstable crack propagation event will define the maximum toughness achieved. However, a small, unstable extension of the crack followed by arrest and further increases in load, termed a *pop-in,* must meet specific criteria to be discounted as the defining load for toughness evaluation.

Fracture toughness depends on the test specimen thickness, B, up to the plane-strain limit, defined as $t = 2.5(K_{Ic}/\sigma_{ys})^2$, as shown in Figure 6.22. This relationship states that the plane-strain limit of material thickness, t, depends on the critical toughness, K_c, and inversely on the yield strength, σ_{ys}, of the material. The Roman

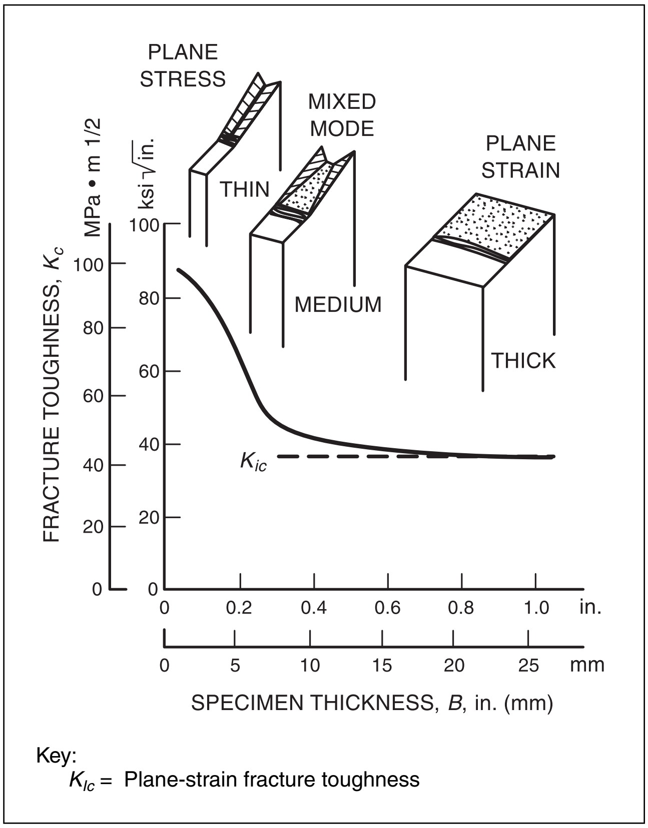


Figure 6.22—Effect of Specimen Thickness on Fracture Toughness for a Relatively Brittle Metal

numeral "I" in the subscript refers to the geometry where the load acts directly to open the crack. Once the specimen is prepared and tested, the resulting toughness, K, and strength are used to calculate a minimum thickness of metal. If the thickness of the test specimen is below this minimum, the crack tip has not been under sufficient constraint to produce plane-strain conditions. Thus, the test is not valid for determining K_{Ic} (i.e., $K_c > K_{Ic}$), and a new test using a thicker specimen would be needed. Most of the common structural and pressure vessel steels are tough and ductile, so valid K_{Ic} specimens can be much thicker than the section sizes actually used.

Materials are typically selected and used in thicknesses that ensure ductile tearing before fracture, i.e., well below the plane-strain limit. The analysis of cracks in such materials utilizes elastic-plastic fracture mechanics. Some EPFM methods, such as the crack tip opening displacement design curve, require only that the test specimen be at least as thick as the thickest section to be used in the structure. Other EPFM methods

25. For more information on fracture mechanics, see Chapter 5, "Design for Welding" in this volume.

incorporate restraint directly to avoid the need to test thicker specimens. The mechanics of testing for these different EPFM specimen types are similar to those used when performing LEFM tests. The publication *Standard Test Method for Measurement of Fracture Toughness*, ASTM E 1820,[26] combines a variety of such evaluations into a single test method, as described later.

Crack arrest tests measure the conditions under which a running crack will stop. Typically, these tests are used to determine the ductile-to-brittle transition temperature (DBTT), below which ferritic steel behaves in a brittle manner. Most other materials, including austenitic stainless steels, do not have a distinct DBTT.

Fracture mechanics methods associated with crack arrest testing include the fracture analysis diagram (FAD).[27] These methods define the DBTT as a single temperature, termed the *nil-ductility transition (NDT) temperature*. The test temperature for production testing is then determined by a temperature shift below the service temperature based on the loading requirements. This temperature shift method has been used as the basis for U.S. Navy and shipbuilding steel selection and to define Charpy V-notch quality control testing requirements.

Tests such as the drop-weight nil-ductility temperature test and the dynamic tear test use a high strain rate and dynamic load on sharply notched, cracked, or embrittled specimens at various temperatures to determine the NDT temperature below which the crack propagates but above which the crack arrests. Similar tests, such as the Charpy V-notch, are performed at various temperatures using notched specimens to provide temperature transition curves to establish the production test temperature.

An example of a Charpy V-notch absorbed energy transition curve is shown in Figure 6.23. As can be observed in this figure, a series of tests are performed at temperature intervals, and the results are plotted against the temperatures. This produces the "S" curve that extends from the "lower-shelf," or lower-temperature region, through the transition temperature and then to the "upper-shelf," or higher-temperature region of high toughness. These ranges are arbitrarily defined, as is the NDT temperature, which is often taken as the top of the lower shelf region.

Finally, individual tests, such as Charpy V-notch, are used as a quality control measure for production. The specimens are small and have a notch but no crack, making the tests more economical to run.

26. American Society for Testing and Materials (ASTM) Subcommittee E08.08, *Standard Test Method for Measurement of Fracture Toughness,* ASTM E 1820, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

27. Pellini, W. S., 1971a, Principles of Fracture-Safe Design. Part I, *Welding Journal* 50(3): 91-s–109-s; Pellini, W. S., 1971b, Principles of Fracture-Safe Design. Part II, *Welding Journal* 50(4): 147-s–162-s; and Pellini, W. S., 1969, *Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures,* Naval Research Laboratory Report 6957, Washington, D.C.: Naval Research Laboratory.

TEST METHODS

Common methods of evaluating the fracture and impact toughness of welded joints include the Charpy V-notch (CVN), plane-strain fracture toughness (K_{Ic}), dynamic tear (DT), and drop-weight nil-ductility temperature (DWNDT) tests. These tests and their rationale are described below.[28]

Charpy V-Notch Impact Test

The Charpy V-notch (CVN) test was developed in 1905 to make qualitative assessments of the influence of notches on the fracture behavior of steels in the transition temperature range. This test procedure, which has gained worldwide acceptance, is employed routinely for steel specification and quality assurance. To determine the energy absorption in fracturing a specimen, this test involves the impact loading of a three-point bend bar that contains a relatively blunt notch. The energy absorbed by the fracture event includes both crack initiation and propagation components, which complicates the interpretation of the results. However, this energy is recorded as part of the test and considered to be a measure of toughness.

The Charpy V-notch impact test is the most common toughness test because it is inexpensive and practical for quality control.[29] The test does not provide fracture toughness directly, but it is often used to specify minimum acceptance criteria for the manufacturing of base and filler metals and to qualify welding procedures.

A Charpy V-notch specimen is shown in Figure 6.24. The specimen, which is not precracked, has a standardized 45°, 0.010 in. (0.254 mm) radius notch. The correct notch tip radius is critical in ensuring consistent results. The tolerance on the radius is ± 0.001 in. (± 0.025 mm).

Routine checks on this tolerance are performed with an optical comparator (shadowgraph) or similar instrument that can magnify the image of the notch tip radius sufficiently for measurement or comparison to maximum

28. For information on the application of test results to weldment design, see Chapter 5, "Design for Welding," in this volume.

29. For further information, see American Society for Testing and Materials (ASTM) Subcommittee E28.07, *Standard Test Methods for Notched Bar Impact Testing of Metallic Materials,* ASTM E 23, West Conshohocken, Pennsylvania: American Society for Testing and Materials; American Society for Testing and Materials (ASTM) Subcommittee A01.13, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A 370, West Conshohocken, Pennsylvania: American Society for Testing and Materials; and American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0, Miami: American Welding Society.

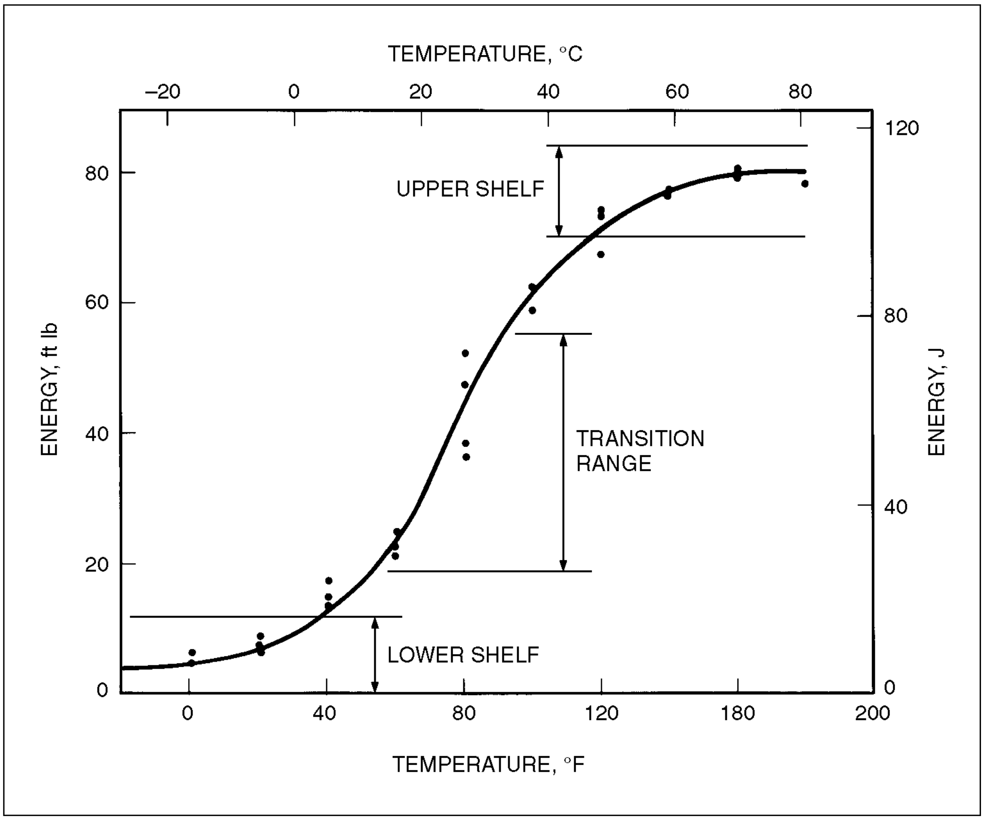


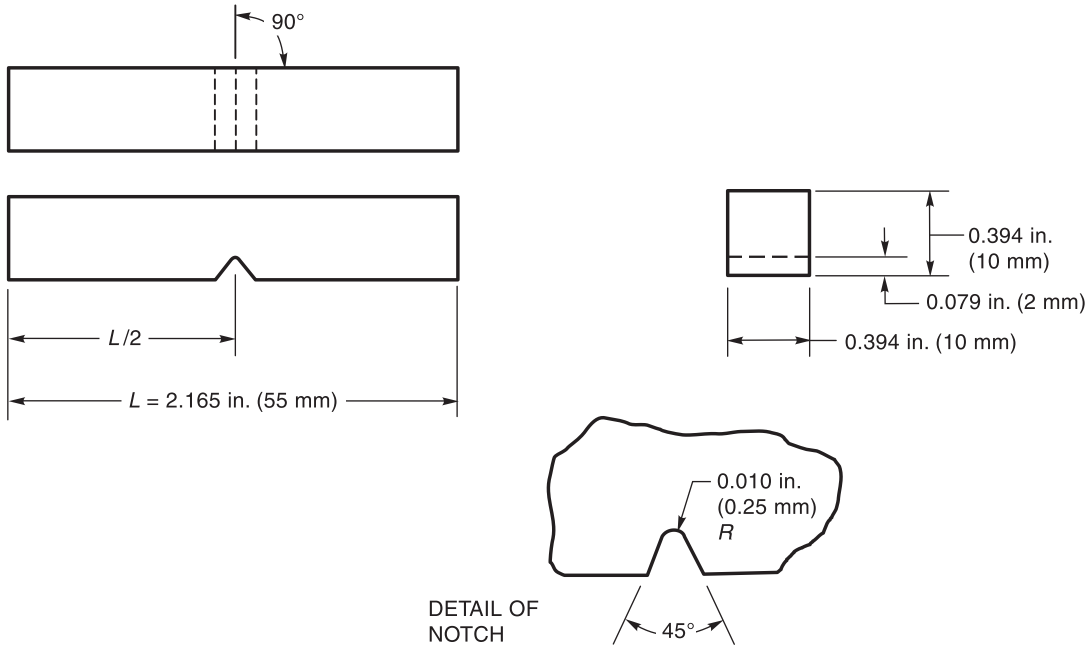
Figure 6.23—Typical Charpy V-Notch Transition Curve for Mild Steel Ship Plate

and minimum radii. Figure 6.25 shows an optical comparator with the notch tip radius on the screen. Calibrated markings on the screen permit the operator to determine whether the notch tolerance has been met.

The specimen is cooled (or heated) to the specified test temperature. It is then placed in the test machine and broken within five seconds. Charpy testing machines use a heavy pendulum to break the specimen. The angle of the pendulum upswing after breaking the specimen is calibrated to measure the energy absorbed by the fracture. Because of the typical scatter in the results, a test requires three specimens, and the average and minimum values are reported. Some specifications require five specimens, in which case the maximum and minimum values are discarded, and the average and minimum values of the remaining three are reported. Specifications for most metals typically require a minimum energy absorption at a particular temperature.

In addition to absorbed energy, the percentage of shear fracture area can be measured and reported. This is evaluated by observing the fracture surface of the specimen and estimating the relative amount of shear fracture, which looks rough and torn, to that of cleavage (brittle) fracture, which appears flat and faceted, or "crystalline." These results are sometimes reported as "percent crystallinity," which is the inverse of the percent shear fracture, although all metals are inherently crystalline, making this a misnomer. Although subjective, fracture appearance is fairly reliable for base metal tests, but the evaluation becomes more difficult for weld metal tests because the columnar weld structure can produce a faceted fracture surface even when exhibiting good toughness.

Lateral expansion is also used to indicate the relative amount of ductile tearing during fracture. Lateral expansion is reported in mils (mm) as the increase in width of the broken specimen over the unbroken width. A brittle specimen will not have significant tearing at the sides of the broken specimen (called *shear lips*), and the width of the broken specimen will be very close to that of the unbroken specimen. A tough specimen will have extensive shear lips that deform the specimen in the width direction. Lateral expansion is less subjective than fracture appearance measures and has been incorporated into codes such as the American Society of Mechanical Engineers' (ASME) *Boiler and Pressure*



NOTE—Dimensional tolerances shall be as follows:

Notch length to edge	90° ± 2°
Adjacent sides shall be at	90° ± 10 minutes
Cross-section dimensions	±0.003 in. (0.075 mm)
Length of specimen (*L*)	+0, –0.100 in. (+0, –2.5 mm)
Centering of notch (*L*/2)	±0.039 in. (±1 mm)
Angle of notch	±1°
Radius of notch	±0.001 in. (±0.025 mm)
Notch depth	±0.001 in. (±0.025 mm)
Finish requirements	63 microinches (2 μm) R_a on notched surface and opposite face; 125 microinches (4 μm) R_a on other two surfaces

Key:
L = Length of specimen, in. (mm)
R = Radius of the notch, in. (mm)

Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 1998, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0, Miami: American Welding Society, Figure A16.

Figure 6.24—Charpy V-Notch Impact Specimen

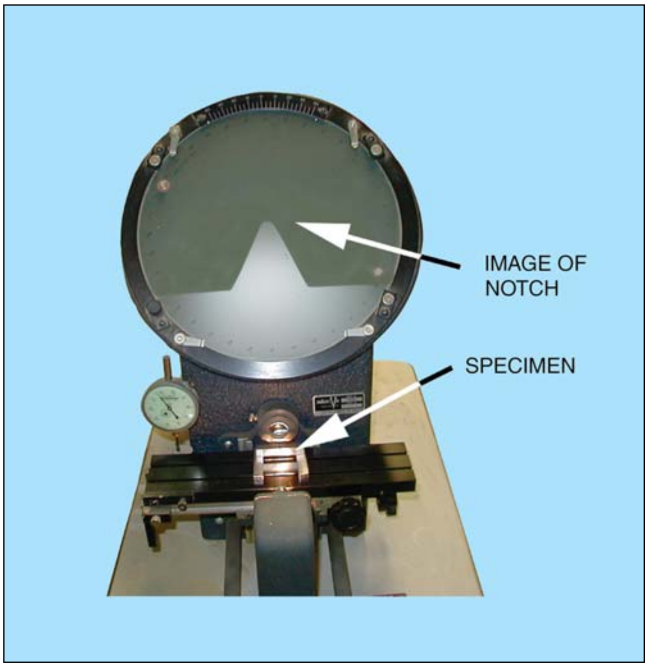
Vessel Code.[30] However, the lateral expansion criteria should be determined for each material.

For metals such as carbon and low-alloy steels that exhibit a change in fracture failure mode with decreasing temperature, it is common to conduct the test at several temperatures to define the ductile-to-brittle transition temperature. Figure 6.23 shows a typical transition temperature curve used with the Charpy V-notch test.

Charpy V-notch transition curves can be constructed from absorbed energy, fracture appearance, or lateral expansion. Although the NDT defined by these curves may differ from that defined by the drop-weight test or other tests that have a sharp starter crack, these curves can provide a single test temperature criterion for production testing.

Some fabrication codes require the determination of the Charpy V-notch energy absorption of the weld metal

30. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, *Boiler and Pressure Vessel Code*, New York: American Society of Mechanical Engineers.



Photograph courtesy of Douglas E. Williams, P.E.

Figure 6.25—Optical Comparator with a Charpy V-Notch Specimen

and the heat-affected zone of the test plate used in the weld procedure qualification. These codes also specify the conditions required, the test temperature, and the minimum acceptable result. In addition, some fabrication codes require that production welds be subjected to impact testing. The production test plates are prepared as runoff plates from a straight seam weld or as separate test plates. However, they should be fabricated at the same time as the production welds and adhere to the same welding procedure specification to be meaningful.

Fracture Toughness Tests

Fracture toughness tests provide designers and engineers a rational means with which to estimate the effects of new designs, materials, or fabrication practices on the performance of structures and their resistance to cracks. As these tests are expensive and time consuming, they are not normally used as an acceptance test for production material or for welding procedure qualification.

Fracture toughness tests provide quantitative data for performing fracture mechanics analyses. LEFM analyses use the results of plane-strain fracture toughness tests (such as K_{Ic}), which require a large enough specimen so that the strain in one of the orthogonal directions (usually the thickness direction) is small relative to the crack size and the specimen dimensions. The minimum test specimen dimensions required to develop a plane-strain condition depend on the ratio of toughness to yield strength and tend to decrease with increasing strength and with decreasing temperature.

On the other hand, EPFM analyses use fracture toughness tests that include significant plasticity, or yielding, during the test. EPFM test results are given in parameters such as the crack tip opening displacement (CTOD) and the J-Curve. The specimens for both LEFM and EPFM tests are similar, but different test analyses and acceptance criteria are employed. In fact, *Standard Test Method for Measurement of Fracture Toughness*, ASTM E 1820[31] allows for either data to be obtained from a single test, depending on the results.

The test sequence employed during fracture toughness testing is as follows. First, a specimen configuration and a test method are selected from *Standard Test Method for Measurement of Fracture Toughness*, ASTM E 1820.[32] This selection is based on factors such as test machine limitations and historical preferences. Figure 6.26 illustrates the compact tension specimen recommended for testing welded joints in *Standard Method for Mechanical Testing of Welds*, AWS B4.0M.[33] The single-edge bend specimen described in ASTM E 1820[34] is also commonly used.

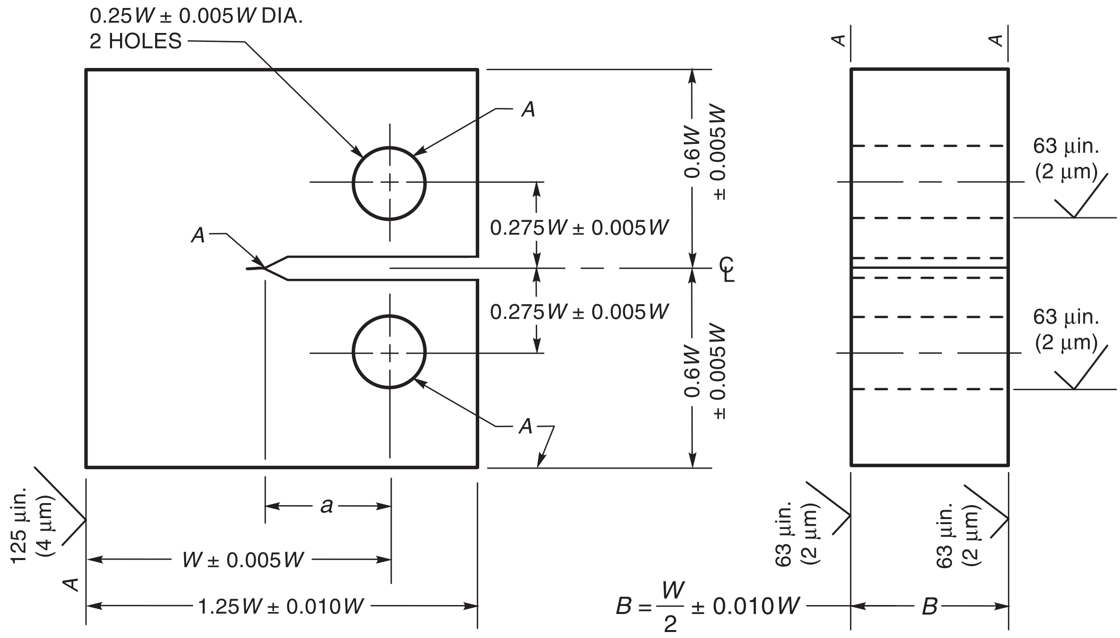
Second, if LEFM toughness is required, a value of the plane-strain fracture toughness, K_{Ic}, is assumed. The value should be overestimated so that the specimen is large enough to meet the specimen size requirements. The minimum specimen dimensions can then be determined. Crack length is found using the following expression:

$$a \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \tag{6.2}$$

where

a = Crack length, in. (mm);
K_{Ic} = Plane-strain fracture toughness, ksi$\sqrt{\text{in.}}$ (N/mm$^{3/2}$); and
σ_{ys} = 0.2% Offset yield strength in tension, ksi (MPa).

31. See Reference 26.
32. See Reference 26.
33. American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0M:2000, Miami: American Welding Society.
34. American Society for Testing and Materials (ASTM) Subcommittee E08.08, 1999, *Standard Test Method for Measurement of Fracture Toughness*, ASTM E 1820-99, West Conshohocken, Pennsylvania: American Society for Testing and Materials.



Note: Surfaces marked *A* shall be perpendicular and parallel as applicable to within 0.002*W* total indicator reading (TIR).

Key:
a = Crack length, in. (mm)
B = Specimen width, in. (mm)
W = Specimen depth, in. (mm)

Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds*, AWS B4.0M:2000, Miami: American Welding Society, Figure A18.

Figure 6.26—Compact Tension Specimen to Determine Fracture Toughness in Weldments

Specimen width is determined as follows:

$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \tag{6.3}$$

where

B = Specimen width, in. (mm);
K_{Ic} = Plane-strain fracture toughness, ksi$\sqrt{\text{in.}}$ (N/mm$^{3/2}$); and
σ_{ys} = 0.2% offset yield strength in tension, ksi (MPa).

Specimen depth is calculated with the following expression:

$$W \geq \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \tag{6.4}$$

where

W = Specimen depth, in. (mm);
K_{Ic} = Plane-strain fracture toughness, ksi$\sqrt{\text{in.}}$ (N/mm$^{3/2}$); and
σ_{ys} = 0.2% offset yield strength in tension, ksi (MPa).

To determine EPFM fracture toughness, such as CTOD, the maximum thickness to be welded in production is often used as the specimen width, *B*. The specimen depth, *W*, is 2*B* for the standard specimen geometries. No criteria for adequate specimen thickness are provided for EPFM analyses because EPFM specimens are assumed to show significant plasticity.

Third, the test specimen is machined, including the notch where the starter crack will be added. The specimen is then precracked by fatigue at a low stress level to provide a sharp starter crack. The test standard specifies the permitted stress level for fatigue cracking and the required size for the starter crack.

Fourth, the specimen is brought to the required temperature and loaded in bending or tension. The load and the crack opening are recorded on an X-Y recorder or electronic media. The specimen is tested to failure, and the maximum load, P_{max}, is recorded. The maximum load may be the load at fracture for a significant fracture instability, the peak load for stable tearing behavior, or the load at pop-in if defined as significant by ASTM E 1820.[35]

Fifth, for EPFM toughness evaluations, the procedures in ASTM E 1820[36] describe the determination of the CTOD, J_{IC}, δ-R curve, or other parameters desired from the final test data.

In the final step in the LEFM determination of K_{Ic}, the load, P_Q, on the load-displacement curve is found using the rules presented in ASTM E 1820,[37] and the ratio P_{max}/P_Q is determined. If the ratio exceeds 1.10, the test is invalid. If the ratio does not exceed 1.10, a conditional plane-strain fracture toughness, K_Q, is calculated using the equations given in ASTM E 1820[38] for the test specimen used.

The expression presented below is then calculated to determine whether the size criteria have been met:

$$2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2 \tag{6.5}$$

where

K_Q = Conditional plane-strain fracture toughness, ksi$\sqrt{\text{in.}}$ (N/mm$^{3/2}$); and

σ_{ys} = 0.2% offset yield strength in tension, ksi (MPa).

If this value is less than both the specimen thickness, B, and the initial uncracked ligament, b_o (equal to the specimen width, W, minus the original crack size, a_o) then K_Q equals K_{Ic}, and the test is valid. If the size criteria are not met, a new, thicker specimen must be tested to provide a valid K_{Ic}.

35. See Reference 26.
36. See Reference 26.
37. See Reference 26.
38. See Reference 26.

Drop-Weight Nil-Ductility Temperature Test

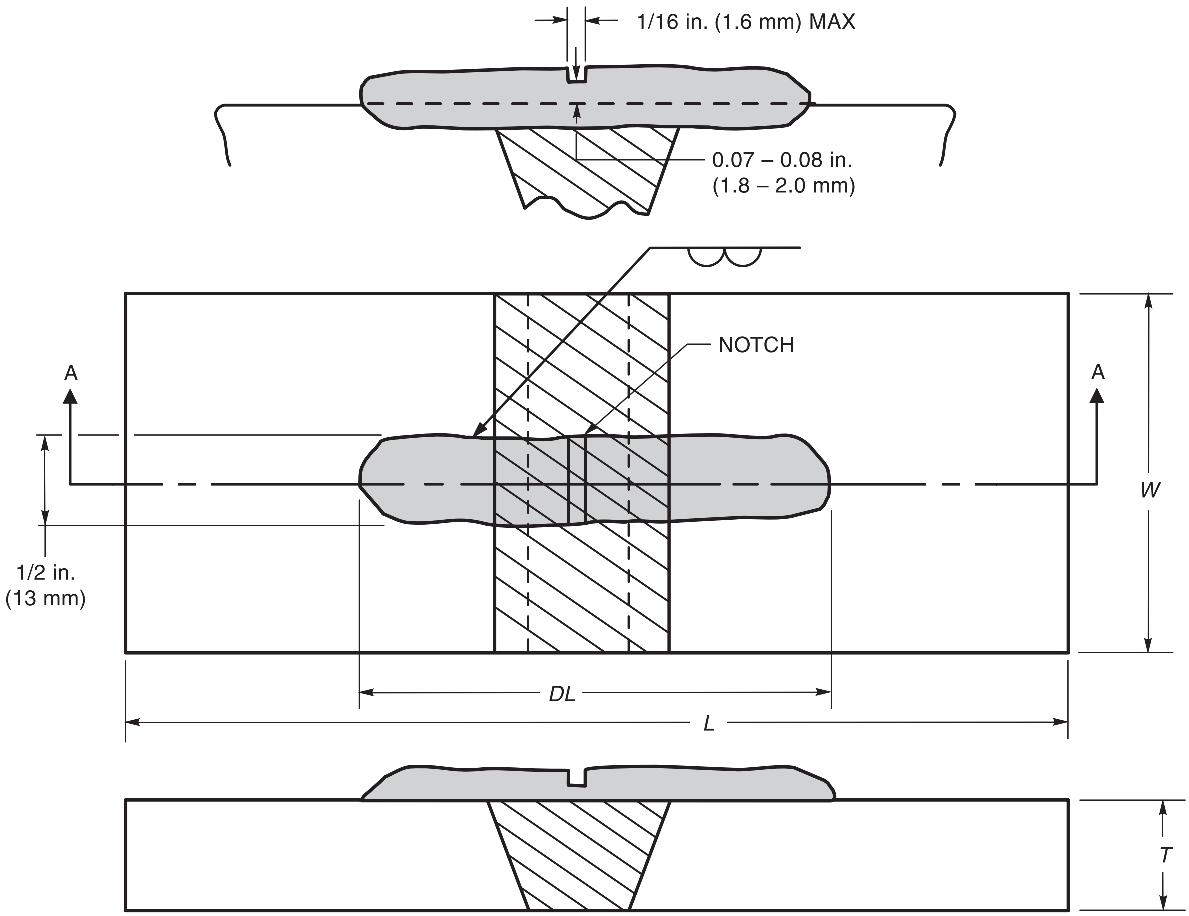
The drop-weight nil-ductility test was created to determine the NDT temperature—the temperature above which a dynamic crack is arrested.[39] The test was developed based on service failures resulting from a brittle fracture initiation at a small flaw located in a region of high stress. To simulate this behavior, a specimen consisting of a small plate section containing a brittle weld region was devised. The specimen is dynamically loaded in bending by a falling weight that causes the specimen to deflect a fixed distance (restricted by "stops"). During the test, the weld is fractured, and the plate is subjected to a small percentage of strain if the base metal does not fracture. As described in more detail below, this test can be used to define the NDT for steels that exhibit a sharp temperature transition behavior. This method is not suited to high-strength steels, which do not have a sharp transition, or steels that develop a tough heat-affected zone below the brittle crack starter weld.

The test comprises dropping a standard weight onto a specimen that has a brittle weld bead. Testing is performed at various temperatures to determine the NDT temperature where "no-break" performance is just exhibited. The procedure for drop-weight weld testing involves welding a brittle crack-starter bead on a test specimen and then notching the weld bead. Standard specimen configurations are shown in Figure 6.27.

The minimum applicable thickness for use in this test is 5/8 in. (16 mm), although a nonstandard 1/2 in. (13 mm) thick plate has also been employed in research and development work. The specimen is chilled to the designated test temperature and tested with the notched bead in tension by applying a load from a falling weight. Deflection of the specimen is limited so that yield-level loading in the presence of the small crack is terminated by the stops. The weight, which totals from 50 lb to 300 lb (22.7 kg to 136 kg), falls from a height to provide a potential energy of 250 ft-lbf to 1200 ft-lbf (340 J to 1630 J). Three standard specimen sizes are defined, and the required potential energy is specified for each combination of specimen size and yield strength.

Upon application of the load, the specimen either breaks or fails to break. If the specimen does not break, the test temperature was above the NDT (the highest tem-

39. For further information on this topic, see American Society for Testing and Materials (ASTM) Subcommittee E28.07, *Standard Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels*, ASTM E 208, West Conshohocken, Pennsylvania: American Society for Testing and Materials; and American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0, Miami: American Welding Society.



Dimensions, in. (mm)			
	P-1 Specimen	P-2 Specimen	P-3 Specimen
T, Thickness	1.0 (25)	0.75 (20)	0.62 (16)
L, Length	14.0 (360)	5.0 (125)	5.0 (125)
W, Width	3.5 (88)	2.0 (50)	2.0 (50)
DL, Deposit length (approximate)	2.5 (64)	1.75 (45)	1.75 (45)

Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds*, AWS B4.0M:2000, Miami: American Welding Society, Figure A19.

Figure 6.27—Standard Drop-Weight Test Specimens

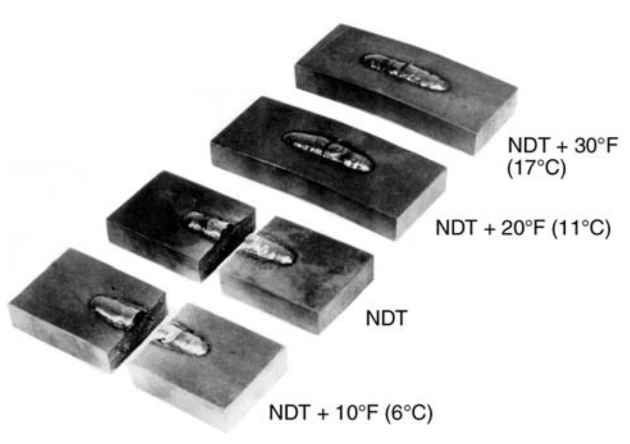


Figure 6.28—Typical Break and No-Break Performances in a Drop-Weight Nil-Ductility Test

perature at which the specimen breaks). Thus, a new test is performed at a lower temperature, generally in 10°F (5°C) increments. A second test is then performed at this temperature to confirm the result. Figure 6.28 illustrates "break" and "no-break" performances.

The drop-weight nil-ductility test is also employed as an acceptance test for steel plates and shapes. When the drop-weight test is used as an acceptance criterion, a temperature is usually specified at which a no-break performance is required based on analyses such as the fracture analysis diagram. This test is often used for the procurement of material for marine applications.

Dynamic Tear Test

The dynamic tear (DT) test was developed in the early 1960s to characterize the fracture properties of ultra-high strength steels, as well as aluminum and titanium alloys that do not exhibit a sharp temperature transition behavior. This test is performed under impact loading, and the resulting absorbed energy at various testing temperatures can consistently define the NDT temperature.

The dynamic tear test specimen is prepared by machining the rectangular shape with the notch geometry. The final notch tip is prepared using a 0.001 in. (0.025 mm) radius hardened knife edge that is pressed into the bottom of the notch to provide a distance of 1.125 in. (28.6 mm) between the notch tip and the back of the specimen. The specimen is then cooled (or heated) to the test temperature and struck by the impact load. The standard specimen is 5/8 in. (16 mm) thick, as shown in Figure 6.29.

The impact load is provided by a falling weight or a pendulum to fracture the rectangular specimen. The specimen has a standardized notch with a sharp tip radius in single-edge notched three-point bending.[40] The standard test is applicable to materials with a minimum thickness of 3/16 in. (5 mm) that have a hardness less than 36 on Rockwell Hardness Scale C (HRC). The dynamic tear testing machine is calibrated to provide the energy absorbed by the specimen, which is reported. The percentage of shear fracture appearance is determined as discussed previously with respect to Charpy V-notch testing.

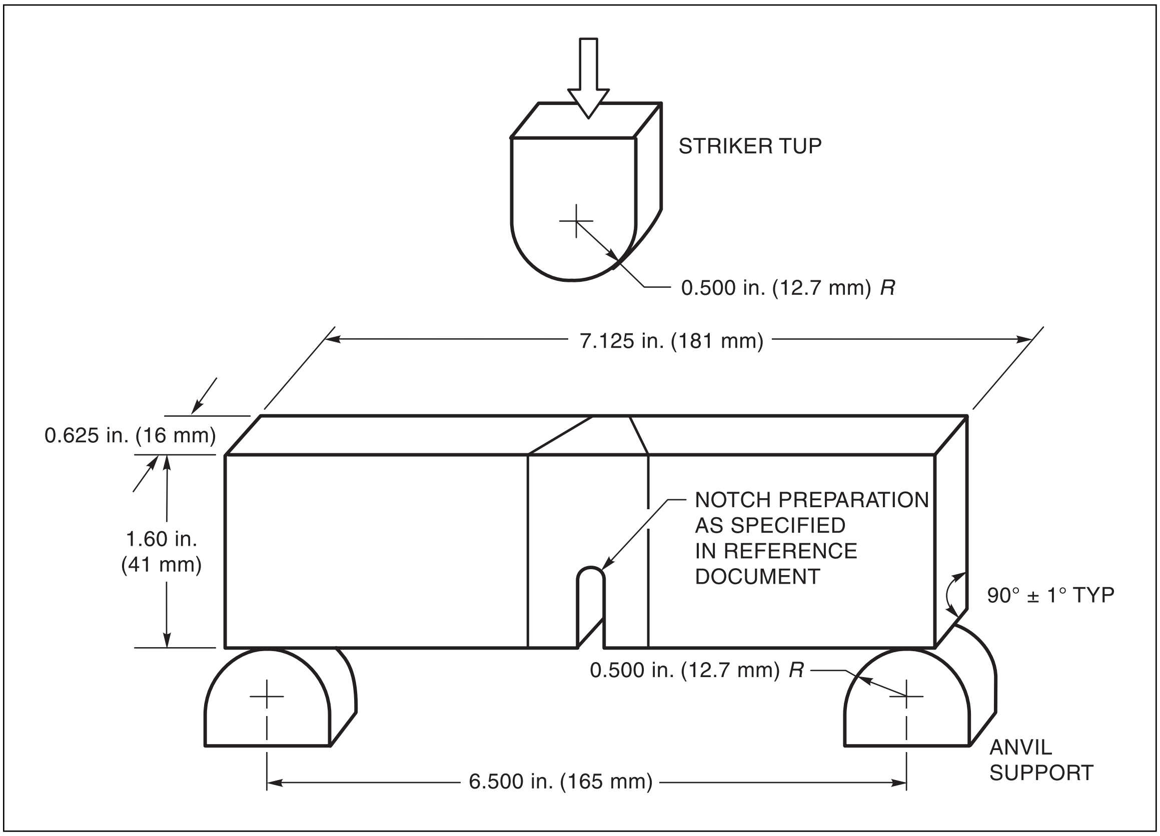
Special Problems in the Evaluation of the Toughness of Welded Joints

As the welded joint contains a wide range of microstructures in the base metal, weld metal, and various heat-affected-zone areas, it presents a special problem in evaluating fracture toughness. For this reason, any test used for this purpose should assess the effect of these varied microstructures and, if possible, assign a relative toughness index to each microstructure. An index establishes the structure that is the most critical, the so-called "weak link," and the relative behavior of each zone.

Whether a weak link will fail in actual service is always uncertain. In some metals, the heat-affected zone is known to be weaker or less tough than the base metal or weld metal. As the heat-affected zone may be rather narrow and irregular, the fracture may not be restricted to this region. Thus, fracture behavior may not reflect the toughness of the heat-affected zone alone. Fracture behavior may also be affected by the portion of the crack front that passes through tougher regions.

Fracture toughness test specimens are suited for testing and evaluating a specific zone because the notch can be located within that specific zone. However, locating the notch of a CTOD or K_{Ic} toughness specimen in a specific weld zone is an exacting task. Moreover, locating the notch does not necessarily control the path of the fatigue crack because residual stresses may cause it to propagate in an undesired direction. This problem

40. For further information on this topic, see American Society for Testing and Materials (ASTM) Subcommittee E28.07, *Standard Test Method for Dynamic Tear Testing of Metallic Materials*, ASTM E 604, West Conshohocken, Pennsylvania: American Society for Testing and Materials; and American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 1998, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0-98, Miami: American Welding Society, Figure A17.

Figure 6.29—Dynamic Tear (DT) Test Specimen Configuration

can persist in spite of prior compression along the axis of the crack to improve the residual stress pattern.

Another problem arises from the fact that toughness tests fail to account for the complex nature of the weld zones themselves. The heat-affected zone—defined as the base metal adjacent to a weld heated by the welding process to a temperature high enough to cause a metallurgical change that could affect the metal's properties—is actually a series of zones caused by the temperature gradient. However, specifications such as those found in Annex III of *Structural Welding Code—Steel,* AWS D1.1:2000,[41] define locations for Charpy V-notch specimens as centered within the weld metal and HAZ. This approach assumes that the test results will reflect the lowest toughness area sampled by the fracture. This assumption is reasonable for weld metal but may not address the "weak-link" issue discussed above. Other approaches have attempted to identify the least tough zone by testing at the fusion line and specified distances (e.g., 1/16 in. and 3/16 in. [2 mm and 5 mm] from the fusion line).

For carbon and low-alloy steels, the heat-affected zone areas are associated with the austenite transformation and possibly with any lower subcritical temperatures at which precipitation can occur. Toughness increases with decreasing grain size. Temperatures that greatly exceed the austenite transition (critical) temperature tend to increase grain size, as in the area directly adjacent to the weld interface. This zone, known as the *coarse-grain area of the heat-affected zone (CGHAZ),* is often associated with the lowest toughness in the heat-affected zone. Slightly farther away from the weld, the temperature just exceeds the critical temperature, resulting in grain refinement. This region, referred to as the *fine-grain area of the heat-affected zone (FGHAZ),* can have better toughness than the unaffected base

41. American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society, pp. 235–237.

metal. Further away in the subcritical area of the heat-affected zone (SCHAZ), where the peak temperature is just below the transformation temperature, the properties may be affected by precipitation reactions in some steels.

The evaluation of these zones to establish the minimum heat-affected zone toughness is described in specifications such as *Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures*, ANSI/API RP 2Z.[42] This specification requires the sectioning of broken CTOD fracture toughness specimens to establish the validity of CGHAZ and other specific HAZ area sampling. The sectioning procedure quantifies the amount of the lower-toughness HAZ regions sampled by the crack. This specification also requires Charpy V-notch transition curves for the CGHAZ and SCHAZ regions to correlate the CTOD results with Charpy V-notch tests, which are more practical for production testing.

In order to provide the CTOD and Charpy specimens that can meet the stringent sampling requirements, a single- or double-bevel weld joint geometry with a very straight HAZ is required. This is difficult to achieve in practice, and additional specimens are often needed to satisfy the HAZ area sampling criteria. Unfortunately, as this is a very expensive and time-consuming process, it is usually warranted only for the characterization of new, ultra-tough materials or for critical applications in which crack growth and high overloads are possible.

Another problem presented by fracture toughness testing is that the heat-affected zone does not exist in isolation; it includes the base metal and weld metal, and each may react differently to stress. A test location must be chosen within the heat-affected zone, or a separate specimen subjected to a simulated weld thermal cycle (see "Weldability Testing" below) must be tested. Such simulated heat-affected zones can be adapted to the Charpy V-notch impact test, but they do not include weld pool effects. However, removing small specimens from welded joints tends to relieve residual stresses and thereby change the fracture characteristics. The best test is one that retains the residual stress pattern around the weld, and such a test requires a large weld specimen. The larger specimen also preserves the elastic constraint of one zone, such as a hard HAZ, on surrounding zones, a feature that may be important in welded joint behavior.

For these reasons, most fracture toughness studies of weldments incorporate many different tests to determine the resistance of the composite weld zone to fracture.

FATIGUE TESTING

When metals are subjected to repeated cyclic stress, they have a tendency to break at a stress considerably below their ultimate strength. The term *fatigue failure* is used to describe the loss of serviceability of a component under cyclic loading at nominal stress levels that would not cause failure if applied slowly and repeated less frequently. Fatigue testing is performed to quantify the fatigue behavior of structural details and, to a lesser extent, the materials themselves.

FUNDAMENTALS

In basic studies of fatigue, failure progression is considered to occur in three stages: crack initiation, crack propagation (or growth), and final fracture. The crack initiation phase is defined by the creation of a crack or by the sharpening of a rounded imperfection into a crack. This process can account for over half of the life of a smooth bar fatigue specimen but is generally not relevant for welded structures because welds contain flaws that are sufficiently sharp to eliminate the entire crack initiation phase.[43] The third stage, which describes the final failure event, is more closely related to fracture than fatigue. Thus, fatigue testing and the design of welded structures are primarily concerned with the second stage, fatigue crack propagation.

Fatigue is a progressive type of failure. It generally originates at a stress raiser—a notch or geometric discontinuity, for example—that causes a stress concentration. In welded assemblies, the discontinuity could be a structural detail, such as an intersection or cover plate, or a material discontinuity, such as a bolt hole or a weld undercut. A fatigue crack develops after many repetitions of the load because the stress concentration increases the local stress. The crack extends with each load cycle until failure occurs or until the cyclic loads are transferred to redundant members. Unlike the static strength of the base or weld metals, a member's fatigue performance is highly dependent on the localized state of stress. Thus, although crack growth rate tests are performed to quantify the fatigue properties of materials, more extensive testing has been performed using welded geometries to obtain stress-cycle curves.

Crack Growth Rate

During the constant growth phase, fatigue cracks grow incrementally for each cycle of stress at a rate that

42. American Petroleum Institute (API), *Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures*, ANSI/API RP 2Z, Dallas, Texas: American Petroleum Institute.

43. Signes, E. G., R. G. Baker, J. D. Harrison, and F. M. Burdekin, 1967, Factors Affecting the Fatigue Strength of Welded High-Strength Steels, *British Welding Journal* 14(3): 108.

depends on the stress range, crack size and, to a lesser extent, the material. This is represented by the following fracture mechanics relationship, which is sometimes referred to as the *Paris law*:

$$\frac{da}{dN} = C\left(\Delta K\right)^n \tag{6.6}$$

where

- da/dN = Incremental crack growth *(da)* for each cycle *(dN)*, in./cycle (mm/cycle);
- C, n = Constants that depend on the material, ratio of maximum to minimum stress (R-ratio), and environment;
- ΔK = Stress intensity factor fluctuation, ksi$\sqrt{\text{in.}}$ (N/mm$^{3/2}$), $= q\ (\Delta\sigma)\ (a\ f)^{1/2}$, where q and f are constants that depend on the crack shape and local geometry, respectively; $\Delta\sigma$ denotes the nominal stress range, ksi (MPa); and a denotes the crack size, in. (mm).

This relationship indicates that the rate of crack growth depends very strongly on the stress range, $\Delta\sigma^n$, and the crack size, $a^{(n/2)}$. Fatigue tests are performed using compact tension or other specimens described above for fracture toughness testing because the stress intensity factor, ΔK, can be determined explicitly from the applied stress range and the specimen geometry. The crack growth rate, da/dN, can be measured directly during testing. The constants C and n can then be determined by plotting the results of many tests on log-log plots. A large number of tests are necessary because of the significant scatter that is typically observed. However, results of tests in air appear to be similar for large groups of materials, and the constants for crack growth in typical (ferritic-pearlitic) structural steels, for example, are similar. [44]

Stress-Cycle (S-N) Curves

Although fatigue data generated from fracture mechanics tests permit the growth of known cracks to be calculated explicitly, this method is not practical for the general design of cyclically loaded structures. The nominal stresses in members and welds are typically determined in the design of structures, but assumptions regarding crack size and geometry are not generally practical to make at the design stage. Thus, various commonly encountered welded geometries have been subjected to cyclic loading at known stress levels to provide data suitable for design. The results are plotted on log-log diagrams as stress-range cycles-to-failure diagrams, termed *S-N curves*, for each category of welded joint.

S-N curves are constructed by means of the statistical analysis of many data points to determine the mean regression line, which represents the most likely result. The number of cycles to failure of a single test piece loaded at a constant stress range provides a single data point. Fatigue behavior varies significantly for each test piece as well as for each structure or component; thus, many tests are required to capture the characteristic response. The line drawn through the average of all data points represents the typical behavior of the specific materials, the test geometry, and environment-to-cyclic loading. The S-N curves used for design, such as those presented in *Structural Welding Code—Steel*, AWS D1.1,[45] represent lower lines that contain the vast majority of the data (e.g., 95% confidence limit for 95% survival).[46] An example of a series of S-N curves is shown in Figure 6.30.

Each data point represents the results at failure for a single test of the specified welded joint geometry cycled at a single stress range. Although different criteria have been used for failure (e.g., the displacement exceeding that of the test equipment), crack growth is very rapid when crack sizes are larger, and variations in the actual criteria used to define failure do not result in large errors in the number of cycles recorded.

Fatigue tests are performed at different stress ranges, and the number of cycles to failure is recorded for each. For steels tested in air, a limiting stress range exists below which fatigue cracking does not occur. These results are considered to be below the endurance limit, and the resulting S-N curve is drawn horizontally at that stress range. However, for fatigue in other environments such as in seawater, the endurance limit may be suppressed or eliminated.

Fatigue Variables

Both the stress range and the design detail affect the fatigue life of welded assemblies. Other factors may influence the fatigue life of unwelded base metals, but their effect on welded assemblies may be minimal. Discontinuities, residual stress, and other inherent characteristics of welds have a greater effect on fatigue life. Figure 6.30 shows S-N curves for rolled and welded

44. Rolfe, S. T., and J. M. Barsom, eds., 1999, *Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics,* 3rd ed., West Conshohocken, Pennsylvania: American Society for Testing and Materials, p. 242.

45. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society.

46. For more information on the manner in which to apply fatigue data to the design of welded girders, see American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel*, AWS D1.1, Miami: American Welding Society.

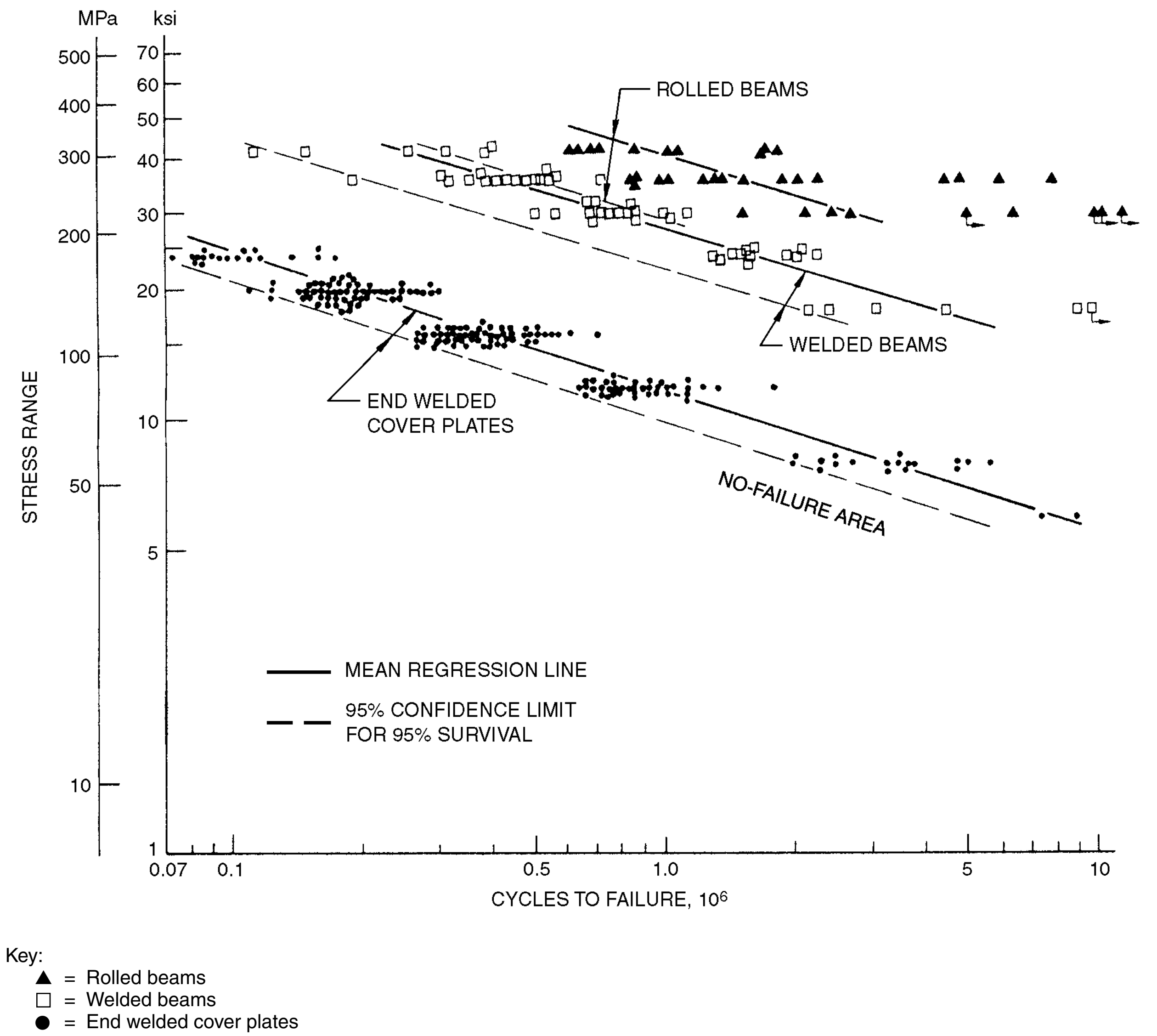


Figure 6.30—Stress Range-Cycle Life (S-N) Relationship for Two Welded Details Compared to Rolled Beams

beams. The figure shows that the average life of a rolled beam subjected to a stress range of 30 ksi (145 MPa) is about 2,800,000 cycles, while the welded beam is only expected to survive 800,000 cycles at the same stress range. Thus, even though the geometries of the specimens were similar, the rolled beam provided over three times the life of the welded beam.

Figure 6.31 illustrates that the minimum stress has no apparent influence on the number of cycles to failure for either a simple welded girder or a cover-plated girder. A compressive or partly compressive stress range may lower the crack growth rate in a plate specimen, but the figure shows no effect for the welded configuration. Welded joints have residual stresses that can be of yield strength magnitude, so any applied cyclic stress can provide an effective stress range with a high tensile mean. Thus, the minimum stress has no apparent effect on fatigue behavior, as shown in Figure 6.31.

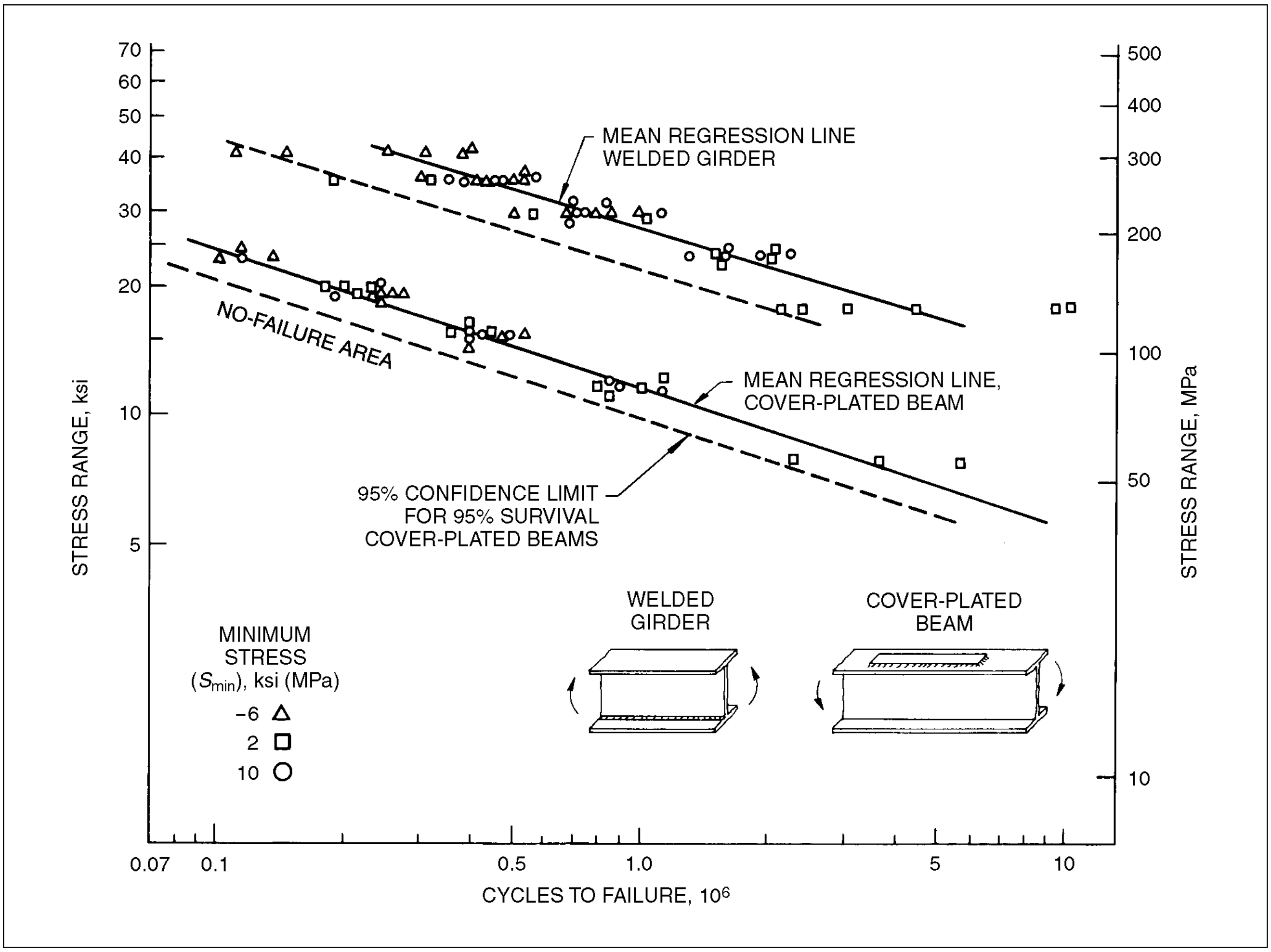


Figure 6.31—Effect of Minimum Stress on the Stress Range-Cycle Life Relationship

Figure 6.32 demonstrates that the grade of steel is not a significant factor in determining the girder life. The three steels represent a wide range of types that have been used in the construction of bridges. ASTM A 36 is a hot-rolled mild steel with a minimum yield strength of 36 ksi (250 MPa), while ASTM 441 has a minimum yield strength of 50 ksi (345 MPa), and ASTM A 514 is a quenched and tempered steel with a minimum yield strength of 100 ksi (700 MPa). No significant difference in fatigue life is evident in the figure. It should be noted, however, that the family of S-N curves for stainless steels, aluminum alloys, and other materials would generally be different.

As shown above, the geometry and the surface conditions of the specimen significantly affect fatigue test results. Weld soundness affects fatigue life because initial discontinuities can provide significant stress concentration effects. The preparation of specimens for fatigue testing should reflect the anticipated specimen geometry and type of inspection. Because natural variations in surface irregularities, weld soundness, and penetration will affect the fatigue life, sufficient specimens must be tested to ensure that the results are statistically significant.

Fatigue is typically dominated by surface discontinuities. When welded fatigue specimens are tested with the weld reinforcement in place, the results show considerable scatter. The fatigue life of specimens with normal weld reinforcement at a given stress range is shorter than that of welded specimens whose reinforcement is ground smooth and feathered into the base plate. This difference in fatigue life is due to the stress concentration of the reinforcement geometry and the smaller size of any preexisting flaw at the toe of the reinforcement.

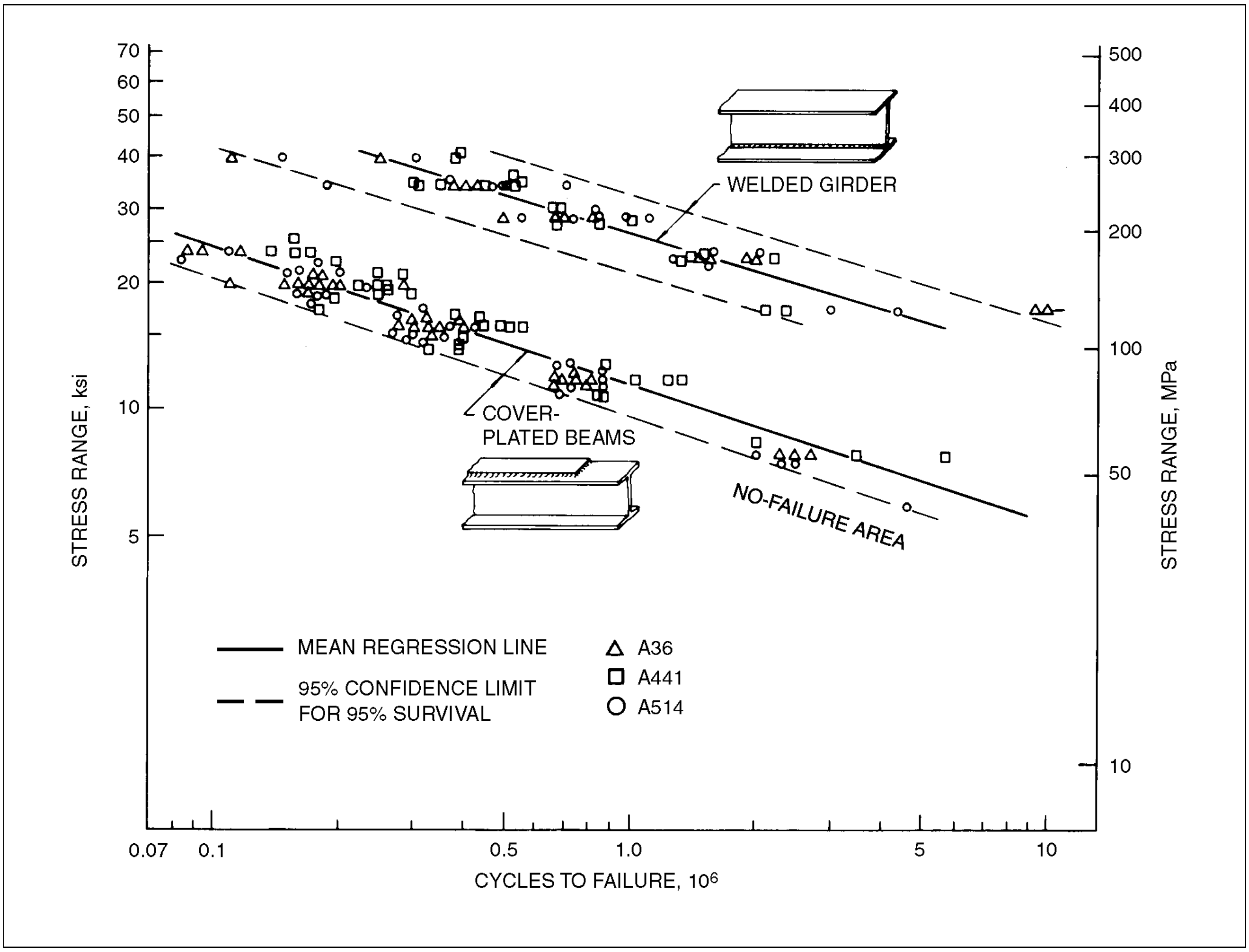


Figure 6.32—Effect of Type of Steel on Stress Range-Cycle Life Relationship

Surface inspection methods such as magnetic particle and liquid penetrant examinations can be used to detect and eliminate larger preexisting flaws that might control the fatigue life of a specific component. The type and extent of any nondestructive examination performed on fatigue test specimens should be recorded along with the acceptance criteria used. It should be noted that codes such as *Structural Welding Code—Steel,* AWS D1.1,[47] provide a more stringent acceptance criteria for visual and nondestructive testing when cyclic loading is specified.

47. See Reference 45.

TEST METHODS

The S-N fatigue properties of base materials can be determined using smooth, round bar specimens that are fixed at one end and strained a uniform amount by a cam on a motor shaft. The smooth bar properties include the complete crack initiation component of fatigue life because a crack must first develop from minute metallurgical changes, such as dislocation movements. Thus, the results are indicative of the fatigue property inherent to the material.

The plain, unwelded surface of a component rarely causes fatigue failure because it is usually near a geometrical discontinuity that acts as a stress raiser and fails in fatigue first. Thus, many different weld geometries are tested in fatigue to quantify the S-N behavior sufficiently for use in design curves. These test specimens have a single weld geometry at the center and are gripped at one end and cycled (by means of a cam actuator, for example) at the other end to produce a known strain at the location of interest. For these tests, the specific geometry, the environment (e.g., air), the stress range, and the number of cycles at failure are reported.

Tests to determine the crack growth rate characteristics of a material are performed using the type of specimens used in fracture mechanics, such as those described above in the section titled "Fracture Toughness Tests." The progress of crack growth at the sides of the specimen is typically measured while the specimen is cycled in the universal tension testing machine. However, this is not usually sufficiently accurate, and the actual crack growth rate is confirmed after the final fracture of the specimen by high-powered microscopic examination of the crack growth striations on the face of the fatigue crack. The results of such tests are reported as crack growth rate constants C and n (see above). Specimen geometry, mean stress, stress ratio, temperature, and for corrosion fatigue, environment and loading frequency should also be reported.

CORROSION FATIGUE

Corrosion fatigue is the result of the simultaneous combination of fatigue stress and an active corrodent upon a metal. The effect of the corrosive media on fatigue life varies depending on factors such as cyclic loading frequency and mean stress, corrosivity, and galvanic or impressed current potential. The result can be a retardation of the crack growth rate if the corrosive media blunts the crack tip or acceleration if, for example, the media dissolves grains or grain boundaries ahead of the crack tip.

Crack growth rates of structural steel in seawater are similar to those in air at loading frequencies down to about 0.1 hertz (Hz) because the corrodent needs time to affect the crack tip. In addition, the mean stress of the stress range can be important because the crack mouth must open sufficiently for the active corrodent to reach the crack tip. Under slow cyclic frequencies and high tensile mean stress cyclic loading, the crack growth rates of steel in seawater are significantly faster than those in air. However, at this slow loading rate, this data is far more expensive to obtain. For example, one million cycles take nearly four months to complete.

The corrosion fatigue of steel in seawater is generally considered to reduce the fatigue limit. This difference in S-N curves for tubular joints can be seen by comparing similar curves in *Structural Welding Code—Steel,* AWS D1.1:2000,[48] and *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms Working Stress Design,* API RP 2A-WSD,[49] where it can be seen that the fatigue limit for the X1 S-N curve in air is approximately 10 ksi (69 MPa) at 10 million cycles, while the corresponding X' curve in seawater is about 5 ksi (34 MPa) at 200 million cycles.

48. See Reference 4.

CORROSION TESTING

The corrosion resistance of welded joints may differ from that of the unwelded base metal because the weld zone varies in chemical composition, metallurgical structure, and residual stress levels. These differences are caused by the welding process itself. Fortunately, the welding process can be controlled and the filler metal can be chosen to optimize the corrosion resistance of welded joints, at least to some extent.

A welded joint and the base metal may corrode uniformly over the entire surface, termed *uniform* or *general corrosion.* Alternatively, the welded joint may be susceptible to different types of preferential attack, as shown in Figure 6.33. This figure schematically represents a macroscopic view of a weldment. Figure 6.33(A) shows uniform corrosion in which all zones of the weldment corrode at the same rate. The weld metal may corrode more, as depicted in Figure 6.33(C), or less, as shown in Figure 6.33(B), than the base metal because of different chemical compositions or microstructures, or both. In addition, as shown in Figures 6.33(D) and 6.33(E), the heat-affected zone may be susceptible to corrosion attack in a specific region as a result of metallurgical reactions during welding.

More than one type of corrosion depicted in Figure 6.33 may occur in the same welded joint. Moreover, microscopic attack—such as intergranular corrosion—and pitting corrosion can occur at any location in a welded joint.

Several factors influence the corrosion resistance of welded joints. These factors should be included in the test report when recording the results obtained in the corrosion tests of welded joints. These include:

1. Chemical composition and structure of base metal and weld metal;
2. Welding process and procedure, especially shielding;
3. Dimensions of the welded test plate and the corrosion specimens removed from the plate;

49. American Petroleum Institute (API), *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design,* API Recommended Practice 2A-WSD (RP 2A-WSD), Dallas, Texas: American Petroleum Institute.

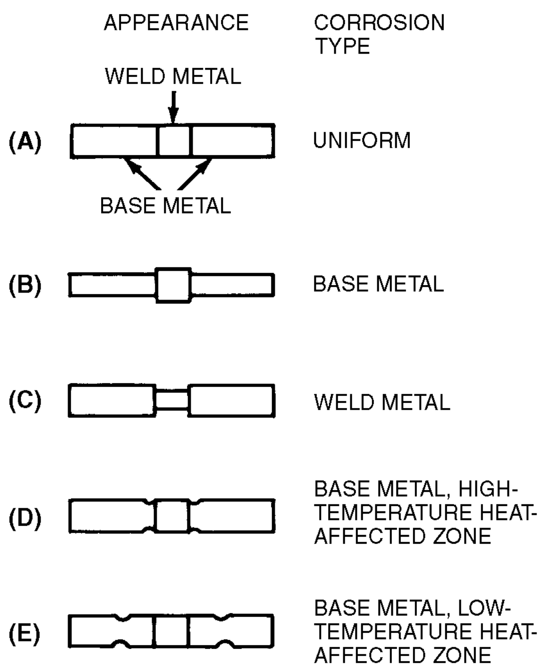


Figure 6.33—Types of Corrosion in a Welded Joint

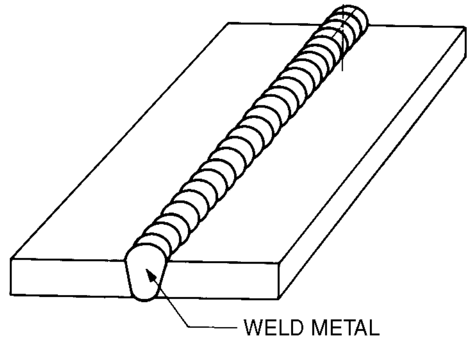


Figure 6.34—Typical Welded Joint Used as a Corrosion Test Specimen

4. Composition, phase, and temperature of the corrosive media; and
5. Details of any galvanic or impressed current cathodic or anodic electrical system used.

TEST METHODS

Various techniques are used to evaluate the corrosion of weldments. For example, weight loss measurements are considered useful because they are generally easy to perform and provide the general corrosion rate directly. In addition, ultrasonic inspection techniques are used to measure localized surface discontinuities and evaluate intergranular attack. However, weight loss tests are generally not sensitive enough to detect other forms of corrosion such as preferential attack, intergranular corrosion, and stress corrosion cracking. Specific tests must be developed for each condition, and a corrosion engineer should be consulted to develop an appropriate test plan.

In all these tests, the corrosion test specimen design varies with the size and type of the product undergoing assessment. When testing for generalized corrosion, a butt joint like that shown in Figure 6.34 is the simplest test specimen shape.

The overall dimensions of the test assembly should be representative of an actual welded assembly, and the thickness should be representative of those used in applications for the material tested. To simulate the residual stresses formed in assemblies, the test plate should be at least 18 in. (450 mm) long and 12 in. (300 mm) wide.

Weld cross sections can also be tested. In some circumstances, the weld metal only is tested. This would be the case when testing the corrosion resistance of a filler metal. It should be noted, however, that this technique cannot determine whether a galvanic corrosion couple will form between this weld metal and a base metal.

The surface preparation of a test specimen should fit the purpose of the test and the technique of evaluating the corrosion damage after the test. However, an effective degreasing method is necessary regardless of the preparation method because grease can provide an effective barrier to aqueous corrodents.

The inspector should adhere to the following guidelines when performing any corrosion test:

1. The specimen should be tested in the as-welded condition with no attempt to remove metal or welding scale. This is recommended when the weld is to be used in service with metal or welding scale and the test environment is identical or similar to that which the weld would experience in service;
2. Unless galvanic corrosion is suspected in the weld, the amount of exposed unaffected base metal should be kept to a minimum; and
3. All surfaces should be machined or ground flush (except in Case 1 above), leaving no undercut or

surface imperfections. These should then be polished to a 120-grit finish. Overheating should be avoided during preparation. This method is recommended if surface examination is to be used for the evaluation. However, the removal of large amounts of weld metal can significantly affect corrosion rates, particularly when working with large sections and multipass welds.

To test a weld with both faces exposed to corrosion, one side of the weld bead can be ground flush, while the other side is left as welded and cleaned. Cleaning can be performed by a mechanical means that does not remove the weld bead, such as shot blasting. Other cleaning methods that involve a descaling or pickling operation, in which both scale and metal are removed, can be used. Normal corrosion test procedures, such as degreasing, are then followed before testing.

For further information on immersion testing procedures, the reader is encouraged to consult the standard *Recommended Practice for Laboratory Immersion Corrosion Testing of Metals*, ASTM G 31.[50]

Weight Loss Test

The most common method of evaluating corrosion resistance is to measure the weight lost during exposure to the corrodent. A sample is prepared and carefully weighed. The surface area that will be exposed to the corrodent is measured after masking off support locations or other areas that would not be exposed directly. Masking should leave a known volume so that the effective weight can be adjusted accordingly. The sample is then subjected to the corrodent for a measured amount of time under either standardized conditions [e.g., see *Standard Practice for Modified Salt Spray (Fog) Testing*, ASTM G 85-98[51]] or actual conditions, such as immersed in the ocean. The weight lost is converted to an average corrosion rate using the following formula:

$$R = \frac{Kw}{ADt} \tag{6.7}$$

where

R = Average corrosion rate in depth of attack per unit time, mils/day (mm/day);
K = Constant;
w = Weight lost by the specimen during the test, ounce (oz) (gram [g]);
A = Total surface area of the test specimen, in.^{2} (mm^2);
D = Density of the specimen material, oz/in.^{3} (g/mm^3); and
t = Duration of exposure, seconds (s).

This formula is intended primarily for general corrosion. However, selective corrosion can also occur in the weld metal or heat-affected zone. Since these areas are small in comparison to the total weld area, the average corrosion rate, *R*, may appear small. Therefore, corrosion test specimens should be examined visually for selective attack, and any localized attack should be reported.

Another technique used to determine whether preferential corrosion has occurred is to expose an unwelded sample of the same dimensions as the welded specimen. If the corrosion rates of the welded and unwelded specimens are approximately equal, no preferential attack is indicated. If one rate is significantly higher than the other, preferential attack should be suspected. A careful visual inspection should always be conducted regardless of the ratio.

The visual examination can be enhanced using macroscopic examination. Low magnification, typically in the range of 1X to 20X, of the tested sample is generally adequate to examine and determine whether a significant localized attack exists. Higher magnifications of up to 100X may also be used, provided the original surface finish of the test specimen permits this.

Several devices may be utilized to measure the depth of preferential attack in a corroded weld. The fine-tipped micrometer is suitable for measuring a severe attack, such as that depicted schematically in Figure 6.33(C). A microscope with calibrated vertical movement can be employed to measure the distance between the top and the bottom of a corrosion pit or a locally corroded zone, such as that shown schematically in Figure 6.33(E).

In addition, a profilometer can be used to scan the surface of a tested sample. This device has a fine needle that moves over the surface of the tested sample. A transducer within the device measures the movement of the needle relative to a flat-tipped shoe and subsurface roughness of the sample can be quantified. Local roughness changes that are associated with weld features such as the heat-affected zone can suggest corrosion mechanisms that warrant further study.

Corrosion is an electrochemical process that is very sensitive to a wide range of variables. Virtually all corrosion tests are developed through careful design to isolate a few variables and evaluate only part of the larger corrosion problem. Thus, corrosion testing is rarely performed during production, and the results must be evaluated with the original objective in mind.

50. American Society for Testing and Materials (ASTM) Subcommittee G01.05, *Recommended Practice for Laboratory Immersion Corrosion Testing of Metals,* ASTM G 31, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
51. American Society for Testing and Materials (ASTM) Subcommittee G01.05, *Standard Practice for Modified Salt Spray (Fog) Testing.* ASTM G 85, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

CREEP AND RUPTURE TESTING

Temperature elevation can affect the performance of metals. When a load lower than that required to produce rapid failure is applied to a metal at an elevated temperature, the metal gradually elongates and ultimately fractures. This gradual elongation or plastic deformation is referred to as *elevated temperature creep*, while the eventual fracture is termed *rupture*.

This time-temperature phenomenon, illustrated in Figure 6.35, occurs in three stages. In the first stage, termed *primary creep*, the rate of extension is high but decreases with time. The second stage of creep is generally an extended period of time during which the rate of extension is constant. In the third stage, the creep rate again increases and eventually ruptures the specimen. Increasing load or temperature, or both, accelerates each stage.

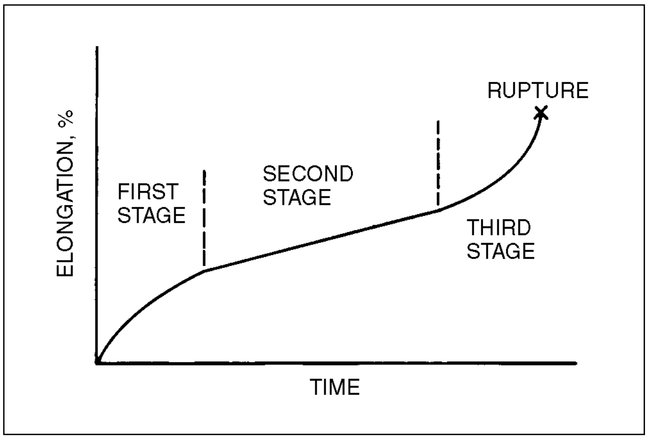


Figure 6.35—Typical Creep Rupture Elongation Curve

TEST METHODS

Two types of tests are typically employed to define creep-rupture properties. The creep test is used to determine the amount of deformation as a function of time. The rupture test measures the time for fracture to occur. These test methods are often combined into a creep-rupture test in which both types of data are obtained. The creep-rupture test measures time to failure at a given applied load, although final elongation and reduction of area are also determined. In any case, testing is performed at a constant tensile force and constant temperature.[52]

The test specimen used to determine creep-rupture strength is a smooth, unnotched specimen that may be an all-weld-metal specimen or a transverse weld specimen. The advantages and limitations of each orientation are similar to those of the tension test, discussed above. However, transverse creep tests are seldom conducted because the variations in elongation in each region of the welded joint render total elongation measurements meaningless.

The testing machine must apply the constant load even as the specimen elongates. Thus, load control must be used with universal tension testing machines. In addition, shock loads, torsion, and bending (e.g., from nonaxially aligned specimens and grips) must be avoided. The apparatus must provide constant temperature control within a few degrees throughout the duration of the test. The extensometer used to record extension must be calibrated to ensure the necessary accuracy at the test temperature.

The specimen is prepared, measured, and placed in the test machine. After carefully aligning the specimen and grips, the extensometer is attached and its output zeroed. The load is then applied rapidly but without shock or other loading transients until the specified load is attained.

Creep data are often reported as a plot of total plastic strain against time on Cartesian coordinates. Rupture data are generally reported on log-log plots of stress versus time to failure, as illustrated in Figure 6.36. The time to failure of each test is plotted against the applied stress, and the best straight line depicting the lower limit of stress is drawn for each test temperature. The time to failure at a constant temperature increases with decreasing stress level and decreases with increasing temperature. The linear relationship between the logarithm of stress and the logarithm of time is reliable provided metallurgical reactions do not occur during the life of the test.

If a solid-state reaction does occur, a relatively distinct change in slope occurs in the curve, as illustrated at points A, B, and C in Figure 6.37. Isothermal reactions in alloy systems are controlled by diffusion. They occur more rapidly at a high temperature than they do at a lower temperature. Thus, the solid-state reactions occurring at points A, B, and C are the same reaction, and a similar reaction should be expected at temperature T_4. However, the time required for the reaction to begin at T_4 may be greater than the life of the test.

52. For further information, consult American Society for Testing and Materials (ASTM) Subcommittee E28.10, *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests in Metallic Materials*, ASTM E 139, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

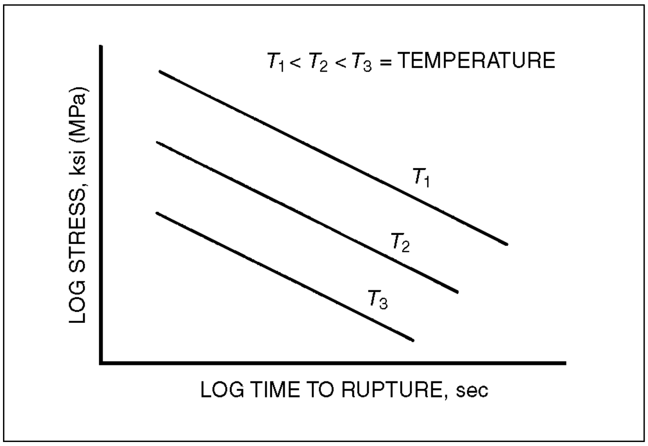


Figure 6.36—Typical Set of Rupture Data at Three Temperatures

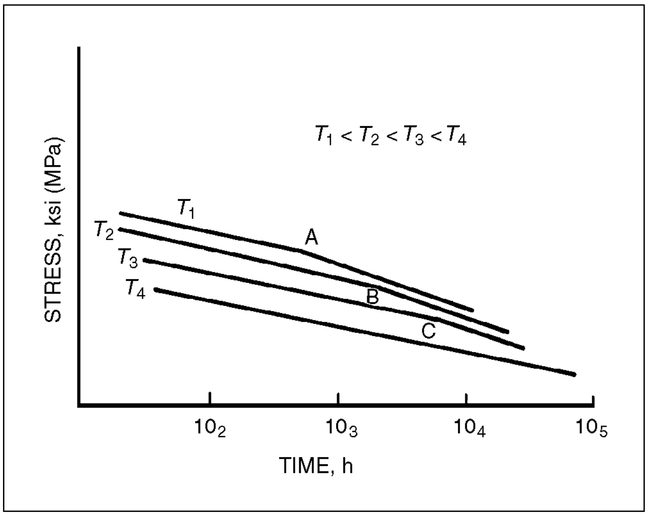


Figure 6.37—Effect of Metallurgical Reactions on the Slope of the Creep-Rupture Curve

Therefore, the results at temperature T_4 should not be extrapolated to longer times.

Parameters have been developed to use high-temperature tests to predict lower-temperature creep performance. Such parameters and their uses are discussed in *Standard Practice for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials*, ASTM E 139.[53]

53. American Society for Testing and Materials (ASTM) Subcommittee E28.10, *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests in Metallic Materials*, ASTM E 139, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

One such parameter, the Larson-Miller parameter, is determined as follows:

$$P = aT\left(C + \log\ t_r\right) \times 10^{-3} \tag{6.8}$$

where

P = Larson-Miller parameter;
a = Constant equal to 1.0 (1.8 with SI units);
T = Absolute temperature, °R (°K);
C = A constant (approximately equal to 20 for most low-alloy steels); and
t_r = Time to rupture, s.

Once the Larson-Miller parameter is determined from several tests, the rupture time for lower temperatures can be estimated directly using this relationship.

TESTING OF THERMAL SPRAY APPLICATIONS

Thermal spray coatings are created by equipment that heats finely divided materials to the plastic or molten state and then propels the material onto a substrate. The high temperature retained at impact causes the individual particles to flatten and conform to the substrate texture and to each other. As the substrate is not melted, thermal spray coatings created by this technique are mechanically bonded to the substrate.

Metallurgical bonding of the thermal spray coating to the substrate is possible using two different methods. In the first, the coating material is selected with self-fluxing characteristics, applied as usual, and then heated in a subsequent process to coalesce within itself and with the substrate. In the second method, the thermal spray equipment, such as a plasma transferred arc, heats the substrate during the application process such that a metallurgical bond is achieved.

Thermal spray coatings range from common metals to plastics, composites, and ceramics. Substrates are most often metals and concrete, but can include wood, cardboard, plastics, or just about any solid matter. Thermal spray coatings are often designed for corrosion control, wear resistance, and machine-element repair and restoration; however, coatings are also applied for electromagnetic shielding, aesthetics, non-stick properties, and many other creative uses. The applicable test methods for a particular coating are highly dependent upon the coating material, substrate, and the objective of the coating design.

Thermal spray coatings may fail tests for a number of reasons. Poor substrate preparation, often in the form of contamination or an improper surface profile for the thickness and type of coating, is a fundamental cause of testing failures. Contamination of the feedstock and, if applicable, compressed air may result in unacceptable performance during testing. Improper machine setup and operation can also lead to failed tests. Finally, unsuitable test selection or unrealistic expectations can return negative indications about an otherwise sound coating.

As a starting point after a testing failure, the feedstock manufacturer's technical data sheets should be consulted to make certain that a properly applied coating has adequate properties to pass the administered test. Diligence in the investigation will yield the real culprit of the failure.

QUALITATIVE TESTS FOR MECHANICALLY BONDED COATINGS

Testing a thermal spray coating applied to a specimen or sample of the product can verify that the thermal spray system, including equipment functions and operation, substrate preparation, the selection of coating material and consumables, are satisfactory. Several tests have been designed to evaluate the properties of the coating materials as well as measure the thickness of the coating and the strength of the bond.

Tape Test

The tape test is a very simple method for determining the thickness of an applied coating. To prepare for the tape test, a piece of tape is applied to the substrate within the coating area or an extra-wide masked region is created on the border of the desired coating area. The thermal spray application is conducted such that the test tape is within the spray pattern.

After the coating has been completed, the test tape is removed, and the thickness of the coating on the tape is measured. If the test tape was not part of the masked region, a spot repair should be applied to the uncoated area.

Magnetic and Eddy-Current Film Thickness Tests

Magnetic film thickness gauges and eddy-current film thickness gauges, commonly used to measure the thickness of paint films, may be used to measure the thickness of some thermal spray coatings on magnetic and nonmagnetic substrates, respectively. The gauges should always be calibrated prior to use.

Thickness readings should be taken along a line at 1 in. (2.5 cm) intervals or randomly located within a 4 in.^{2} (25 cm^2) area. One thickness measurement is the average of five readings by a single method. Line measurements are generally used for large, flat areas, while area measurements should be used on corners, curves, and other complex geometries.

Cut Test

The cut test is a simple test used to evaluate the bonding of the coating to the substrate. The test is conducted by making a single cut through the coating. The cut should be approximately 1.5 in. (4 cm) long and should not severely cut into the substrate. The cut should be created with a sharp edge tool such as the pull cutting tool (per *Metallic and other Inorganic Coatings—Thermal Spraying—Zinc, Aluminum and their Alloys*, ISO 2063[54]), a hammer and chisel at a shallow angle, or a knife. Properly bonded coatings adhere tightly along the cut. The cut test is described in the above-referenced standard and in the *Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites*, ANSI/AWS C2.18.[55]

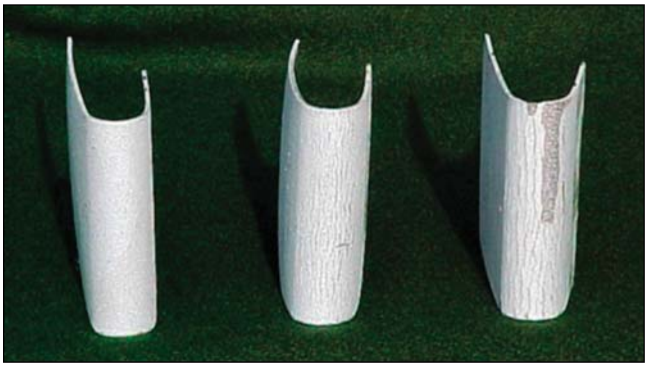
Bend Test

The bend test is a simple method to verify the proper behavior of the thermal spray system, including substrate preparation, the condition of the feedstock, the setup and functioning of the equipment, and operation. A coupon approximately 2 in. by 4 in. by 0.050 in. (5 cm by 10 cm by 0.125 cm) is prepared from the same material and conditioned in the same manner as the substrate. The large face of the coupon is sprayed per the application procedure. The coupon is bent 180° around a mandrel with the coating on the tensile side. The coating is inspected visually without magnification.

As shown in Figure 6.38, an acceptable coating may be uncracked or have small hairline cracks in the vicinity of the bend, but no flaking, delamination, or gross cracking of the coating should be visible. The diameter of the mandrel appropriate for testing a particular coating will depend upon the coating material, thermal spray process, and coating thickness. Extremely thin or thick coatings may have to be tested at a thickness other than that of the specified coating. Further information is presented in the *Guide for the Protection of Steel*

54. International Organization for Standardization (ISO), *Metallic and Other Inorganic Coatings—Thermal Spraying—Zinc, Aluminum and their Alloys*, ISO 2063, Geneva: International Organization for Standardization (ISO).

55. American Welding Society (AWS) Committee on Thermal Spraying, *Guide for Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites*, ANSI/AWS C2.18, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Task Group A, Process Specification, 20XX, *Guide for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and their Alloys and Composites for the Corrosion Protection of Steel*, ANSI/AWS C2.18A-20XX, Miami: American Welding Society, Figure 1.

Figure 6.38—Bend Test Specimens: Examples of Pass and Fail

with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites, ANSI/AWS C2.18.[56]

Companion Coupon Test

The companion coupon test is a variation of the bend test. It is used to evaluate an as-applied coating. The coupon is prepared as for the bend test, but instead of being sprayed independently, it is attached to the substrate within the coating area or immediately adjacent to the coating area in a masked region. The thermal spray application is conducted such that the coupon lies within the spray pattern. The coupon is removed, bent, and evaluated as is done in the bend test. If the coupon was not part of the masked region, a spot repair should be applied to the uncoated area.

Bar Stock Test

The bar stock test is useful for evaluating the overall characteristics of a thermal spray coating that will be machined or otherwise finished. A 3 in. (7.5 cm) diameter by 10 in. (25 cm) bar of the substrate material is used. The middle 6 in. (15 cm) of the bar is machined to reduce the diameter by 0.040 in. (0.1 cm). The exact radius of the bar should be recorded prior to the thermal spray application. The bar is sprayed per the application procedure. The thickness of the applied coating is determined by comparing the radius of the bar before and after the application, and the thickness of each coating pass can be determined through intermediate measurements, if desired.

The coating, which is examined visually, should exhibit a smooth texture. Unacceptable characteristics include cracks, lumps, dust, debris, inclusions, blisters, and other irregularities. The coating on the bar should be finished in a manner that resembles the production component as closely as possible. The finished coating should have a clean surface without particle pullouts, pits, cracks, or other irregularities.

QUANTITATIVE TESTS FOR MECHANICALLY BONDED COATINGS

Various quantitative tests have been developed to evaluate mechanically bonded coatings. The most commonly applied tests are described in this section.

ASTM C 633 Adhesion or Cohesion Strength Test

The publication *Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings*, ASTM C 633,[57] details a test method for the determination of the tensile bond strength of a thermal spray coating design. The thermal spray coating is applied to a substrate fixture of the same material and surface condition as the intended production component. The coating may be ground or otherwise finished to square the coating with the substrate fixture and remove thickness variations. The finished thickness must be at least 0.015 in. (0.038 cm). A loading fixture that is geometrically identical to the substrate fixture is prepared and adhesively bonded to the thermal spray coating on the substrate fixture. The fully cured assembly is attached to a tension testing machine with self-aligning devices that transmit only tensile load and prohibit eccentric loads or bending moments to the assembly.

The testing machine applies an increasing load at a constant cross-head travel rate until rupture occurs. The testing machine registers the maximum load before rupture. Tensile strength equals the maximum load divided by the cross-sectional area. The adhesion strength of the coating is determined if the failure is entirely on the coating-substrate interface. The cohesive strength of the coating is determined if the failure is entirely within the coating. Failure of the bonding agent shows only that the adhesion and cohesive strength of the coating is at least as great as the bonding agent, which may be satisfactory depending upon the load at which the bonding agent failed. Failure in a combination of these locations is inconclusive. A minimum of five samples are recommended.

56. See Reference 55.

57. American Society for Testing and Materials (ASTM) Subcommittee B08.14, *Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings*, ASTM C 633, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

ASTM D 4541 Pull-Off Strength Test

The publication *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*, ASTM D 4541,[58] details a test method for the determination of the tensile bond strength of a thermal spray coating. The self-alignment adhesion tester type IV, described in Annex A4 of this standard,[59] is the preferred type of portable adhesion tester for use with thermal spray coatings. The thermal spray coating is applied to the substrate per the application procedure. A loading fixture, also referred to as a dolly, stud, or slug, is secured to the coating with a bonding agent and allowed to fully cure. The testing apparatus is attached to and aligned with the loading fixture. An increasing load is applied to the fixture until rupture occurs and the maximum load is recorded.

Tensile strength is determined from the conversion chart for the loading fixture used for the test. The adhesion strength of the coating is determined if the failure is entirely on the coating-substrate interface. The cohesive strength of the coating is determined if the failure lies entirely within the coating. The tensile strength of the substrate is determined if the failure lies entirely within the substrate. Failure of the bonding agent shows only that the adhesion and cohesive strength of the coating is at least as great as the bonding agent, which may be satisfactory depending upon the load at which the bonding agent failed. Failure in a combination of these locations is inconclusive. A nondestructive test can be attempted by loading the tensile fixture to a specified value. A minimum of three samples should be taken in a localized area, and the average of the results is considered a single measurement.

TESTS FOR MECHANICALLY OR METALLURGICALLY BONDED COATINGS

Several test methods have been developed to assess mechanically or metallurgically bonded coatings. Among these are metallographic examination and the service life test, which are described below.

Metallographic Examination

Metallographic examination of transverse specimens through the coating and into the substrate can provide valuable information about a coating. Considerable care must be exercised during the mounting and polishing of the sample as improper procedures may taint the results. Experience is required in order to discern coating porosity and oxides from pullouts and other sample preparation artifacts which may exist even in properly prepared specimens. Porosity and oxide levels are usually determined by line-intercept, grid-area, or image analysis techniques or by comparison charts. Acceptable coating morphology (allowable interface contamination, cracks, porosity, oxides, and unreacted particles) is usually specified in overhaul manuals for critical components as well as in the feedstock manufacturers' technical data sheets.

Service Life Testing

Service life testing can provide valuable information about the effectiveness and service life of a coating in various environments. Simulated service, accelerated simulated service, and actual service tests each offer benefits depending upon component criticality, the cost of testing, the cost of failure, available time, and many other factors.

The efficient design of service life tests is critical to their cost and effectiveness. Unlike the aforementioned tests—which attempt to relate an isolated, measurable coating characteristic to fitness-for-purpose—service life testing can bring together many or all of the complex factors that determine the success of a coating in a particular environment and should be carefully considered.

WELDABILITY TESTING

The term *weldability* refers to the relative ease with which a material can be welded using specific procedures to provide the intended service. Weldability is affected by all of the significant variables encountered in fabrication and service. These variables include joint restraint, fitup, surface condition, erection, and service stresses. Many variables exist in the design, fabrication, and erection of actual structures, and no single test or combination of tests can completely simulate all of the real conditions. Furthermore, these variables may be different for each assembly in a structure. Therefore, laboratory weldability tests can only provide a means for comparing different metals, procedures, and processes. The data should be used in comparison to the weldability of existing alloys, procedures, or processes for which the fabrication and service performance is known. The results are only qualitative, and laboratory testing, regardless of the extent, cannot quantitatively predict fabrication experience. Notwithstanding its lim-

58. American Society for Testing and Materials (ASTM) Subcommittee D01.46, *Standard Test Method for Pull-Off Strength of Coating Using Portable Adhesion Testers*, ASTM D 4541-95E1, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
59. American Society for Testing and Materials (ASTM) Subcommittee D01.46, 1995, *Standard Test Method for Pull-Off Strength of Coating Using Portable Adhesion Testers*, ASTM D 4541-95E1, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

itations, weldability testing provides valuable data on new alloys, welding procedures, and welding processes.

Numerous weldability tests that focus on the base metal, heat-affected zone, or the weld metal have been devised. These can be classified as either simulated or actual welding tests. The most commonly used tests are described.[60] Specific issues concerning the base metal's response to welding are discussed below.

EVALUATION OF THE HEAT-AFFECTED ZONE

The response of the base metal to the heat and stress of welding can be evaluated using either simulated or actual heat-affected zones. Procedure qualification tests are based on the pragmatic view that the test weld should resemble the production weld as closely as possible. As heat-affected zones are small, such tests sample not only all of the subzones, e.g., the coarse grain heat-affected zone (CGHAZ), the fine-grain heat affected zone (FGHAZ), and the subcritical heat-affected zone (SCHAZ) but also the weld metal and unaffected base metal as well.

Weldability tests of base materials, on the other hand, are used to determine their response to the temperature and stresses imposed by the welding cycle, so it is useful to isolate these regions for characterization and testing. This can be accomplished by simulating the heating and cooling cycles of a weld, either in an unrestrained condition or subjected to stresses that simulate those of a highly restrained weld. The susceptibility of regions of the heat-affected zone to cracking, embrittlement, or other welding problems can also be isolated by carefully designed actual welding tests, such as those described in subsequent sections.

The actual heating and cooling rates that can occur in the heat-affected zone of a weld can be very high, and specialized equipment has been developed to simulate this effect. The most common systems are the Gleeble® simulators. The basic Gleeble system subjects the entire cross section of a metal specimen to heating, holding, and cooling cycles that can be programmed to simulate any region in the heat-affected zone. This apparatus has been used to study the response of many materials to the weld thermal cycle.

Similar systems that can impose significant strains on the specimen during the preprogrammed thermal cycle are also available. This equipment can simulate single and multiple pass weld thermal and stress cycles and provide specimens with sufficiently uniform properties so that representative testing and evaluation are possible. Hardening, embrittling, and cracking mechanisms can be isolated and studied using this method. However, except for liquation cracking of a partially melted zone, these simulations do not include a molten weld pool. Thus, the effects associated with the weld pool, such as base metal dilution, must be evaluated by welding.

WELDING TESTS

A variety of actual welding tests have been devised to investigate the weldability characteristics of base and weld metals. In general, base metal tests serve two purposes. First, they can be used to evaluate the weldability of particular grades or individual heats of base metals. For this purpose, the specimen dimensions and welding conditions remain constant to make the base metal sample the only variable. They can also be used to establish compatible combinations of base metal, filler metal, and welding conditions that will produce acceptable welds based on the test results.

However, most weldability tests are developed to evaluate a specific problem area. The tests described below address the following weldability problems: hot cracking, root cracking, and hydrogen-induced cracking.

Hot Cracking Tests

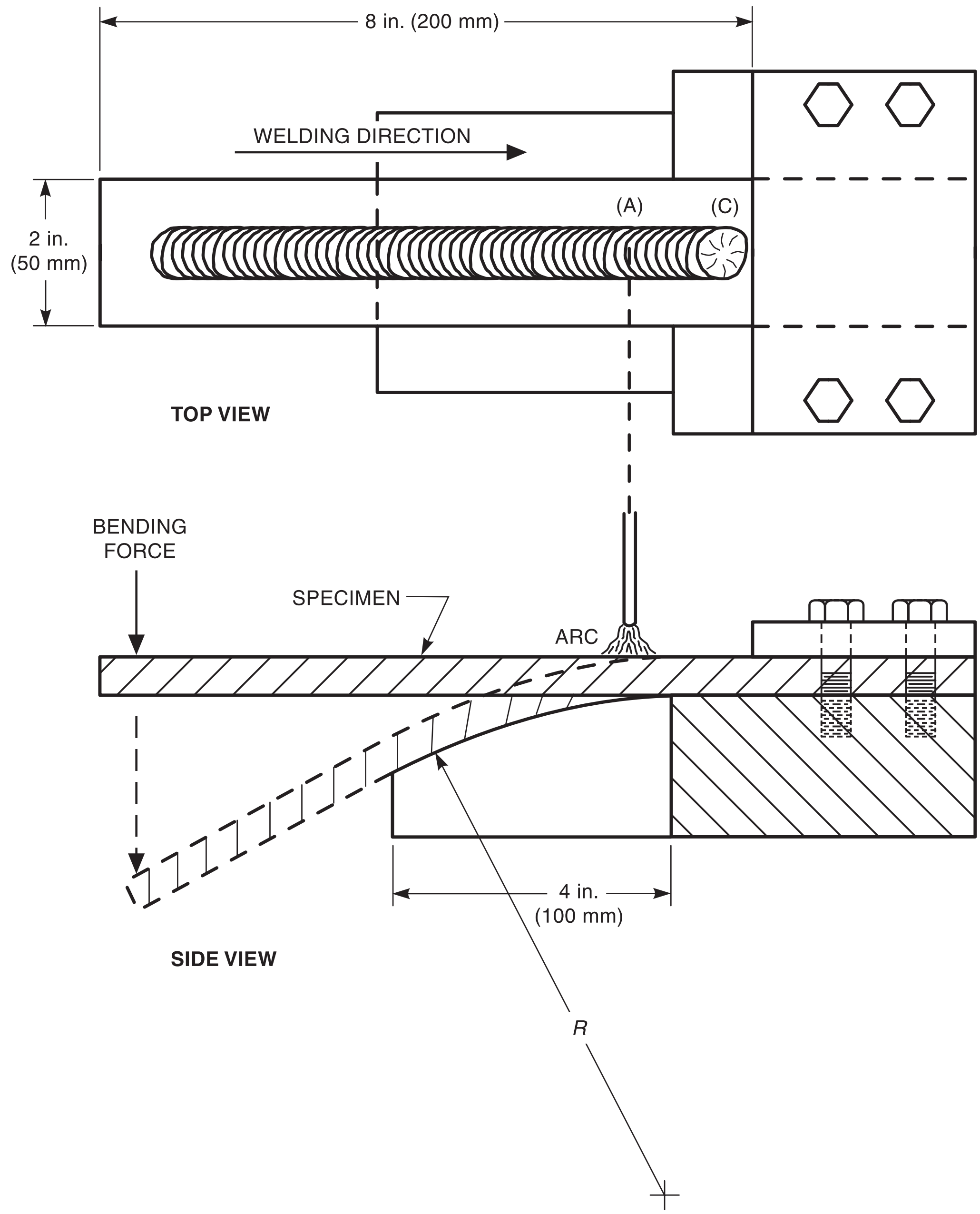
Hot cracks are formed at high temperatures and are often the result of solidification segregation and shrinkage strains. Although several tests have been devised to study hot cracking, these tests use either an imposed load during welding or the shrinkage strains from an adjacent weld to force hot cracking.

Varestraint Test. The varestraint test is one of the most commonly employed to evaluate hot cracking. This test, shown in Figure 6.39, utilizes external loading to impose plastic deformation in a plate while an autogenous weld bead is deposited on the long axis (longitudinal) or short axis (transverse) of the plate. The severity of deformation is varied by changing the bend radius. The magnitude of strain that causes cracking is an indicator of the crack susceptibility of the base metal.

Figure 6.40 shows a varestraint test in progress. A test specimen is about to be welded with the gas tungsten arc welding process, while the specimen in the foreground has already been welded and bent.

Upon cooling, the weld is examined for cracks using a low-power microscope. Three criteria—the cracking threshold, the maximum crack length, and the total combined crack length—are used to evaluate test data.

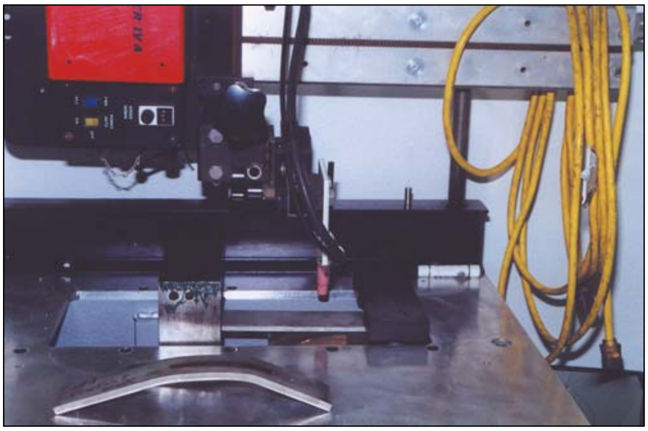
60. For further information on weldability testing, refer to American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0, Miami: American Welding Society, and American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds*, AWS B4.0M, Miami: American Welding Society.



Key:
(A) = Point of progression at which the bending force is applied
(C) = Location of the termination of the test weld
R = Die block radius

Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds*, AWS B4.0M:2000, Miami: American Welding Society, Figure E15.

Figure 6.39—Longitudinal Varestraint Test Fixture and Specimen



Photograph courtesy of LeTourneau University

Figure 6.40—Varestraint Test in Progress

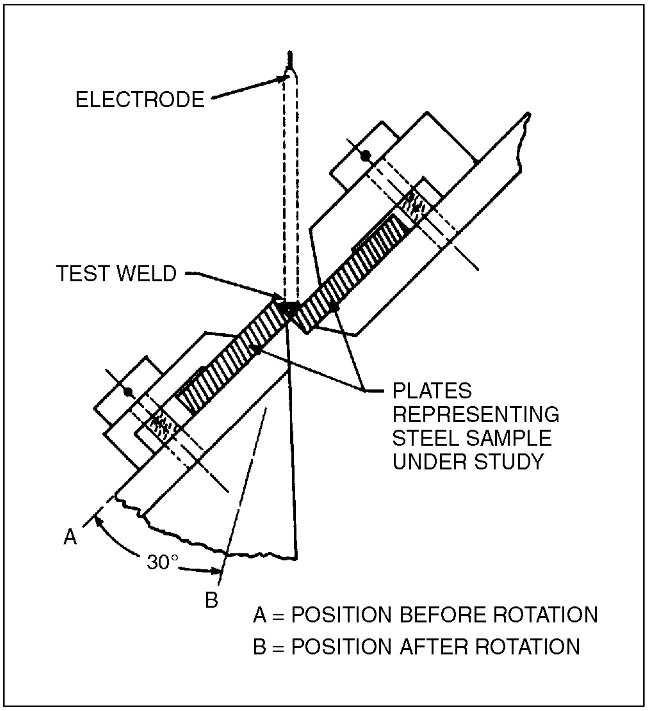


Figure 6.41—Murex Test

The cracking threshold, the minimum strain required to cause cracking in a base metal welded with a given set of welding variables, provides a means to compare welding procedures. The maximum crack length is used when evaluating metals for crack sensitivity. The total combined crack length, obtained by adding the lengths of all cracks present in the weld metal and the heat-affected zone, furnishes the best quantitative index of hot cracking.

Gleeble Hot Ductility Test. The Gleeble apparatus is also used to perform the Gleeble hot ductility test. The purpose of this test is to characterize the susceptibility of the heat-affected zone of alloys to liquation cracking of alloys by their hot ductility response. The specimen is heated and strained in the Gleeble equipment.

The results are evaluated based on the reduction of area exhibited by specimens fractured at various temperatures during the "on-heating" and "on-cooling" cycles of the weld thermal cycle. The ductility is determined from the tensile load required to fracture the specimen at a specified temperature during the two portions of the thermal cycle.

Murex Test. The Murex test, illustrated schematically in Figure 6.41 is conducted on two plates that are welded while mounted in a fixture that can rotate one of the plates at various speeds while welding. Susceptibility to hot cracking is indicated by the extent to which the weld metal cracks at various rates of strain during solidification.

T-Joint Test. The T-joint test, shown in Figure 6.42, utilizes a restrained T-joint configuration to measure the cracking tendency in a fillet weld. The second bead is deposited immediately following the first on the other side so that the rotation strains generated by the contraction of the first bead are imposed on the second bead during deposition. The test is evaluated by determining the extent of the cracking.

Root Cracking Tests

The root pass of a weld is subject to the most onerous conditions of any pass in a weldment. This pass ties two pieces together and therefore must accommodate the shrinkage strains alone. Shrinkage strains begin as soon as the weld can sustain stress, which may occur even before the weld is fully solidified. Although the direct paths for heat flow are limited by the small weld cross section, the small size of the root pass can produce high cooling rates in the adjacent heat-affected zone, which can increase the susceptibility to cracking in hardenable base metals.

Moreover, this limited cross section can concentrate hydrogen from the weld into susceptible areas of the heat-affected zone. Finally, the method of shielding atmospheric contaminants by most welding processes is not as effective on the back side of the root, particularly for open root weld joint configurations. The

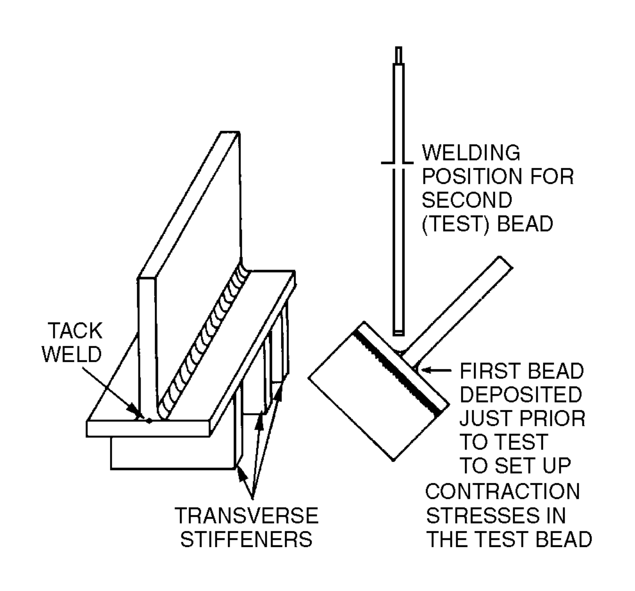


Figure 6.42—T-Joint Test

contamination of the weld metal with nitrogen, along with the inherent straining from weld contraction, can cause strain-age toughness degradation in this critical area. Thus, the root pass has been an area of interest in weldability testing. Most tests that evaluate root cracking can also provide information about cold cracking and other problems, as discussed later.

Lehigh Restraint Test. The Lehigh restraint test can impose a controllable severity of restraint on the root bead deposited in a butt weld groove with dimensions to suit the application. A series of test pieces that have varied depths of the side slits can be tested to determine the critical cracking restraint for the specific welding conditions. This test utilizes a test specimen measuring 8 in. by 12 in. (200 mm by 300 mm), as shown in Figure 6.43. The degree of restraint is reduced by cutting slots along the long edge of the plate, whereas it is increased by reducing the weld groove length or by increasing the specimen size.

In the standardized test described in *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0-98[61] and AWS B4.0M:2000,[62] the weld is first performed on plate without slots, and slots are subsequently added (and then deepened) in successive trials until no cracking is observed. After cooling, the specimen is examined visually for cracks on the surface of the weld. Liquid penetrant or magnetic particle testing should be conducted to verify the absence of cracks, if necessary.

Circular Patch Test. The test specimen used for the circular patch test is comprised of a plate with a circular hole cut into it and a patch fitted to create a circular weld groove, as shown in Figure 6.44. When a weld bead is deposited, the circular configuration magnifies the stresses placed on the weld metal because of thermal contraction. Restraint can be increased in a given plate thickness by increasing the plate size and reducing the patch diameter. The results are evaluated by observing the extent of cracking.

Hydrogen-Induced Cracking Tests

Hydrogen-induced cracking, also known as delayed cracking, requires three conditions: a susceptible microstructure, the presence of hydrogen, and tensile stress. The residual stress from welding on a restrained joint generally provides sufficient tensile stress in practice, and hydrogen is introduced with the weld process. The susceptibility of steel materials to hydrogen-induced cracking can depend on hardenability and other metallurgical factors, so the base metal is often the subject of research. However, the crack resistance of the weld metal is of equal importance, and these tests are applicable to both.

The test methods used to assess hydrogen-induced cracking include the Lehigh restraint test, discussed above, the controlled thermal severity test, the cruciform cracking test, and the implant test.

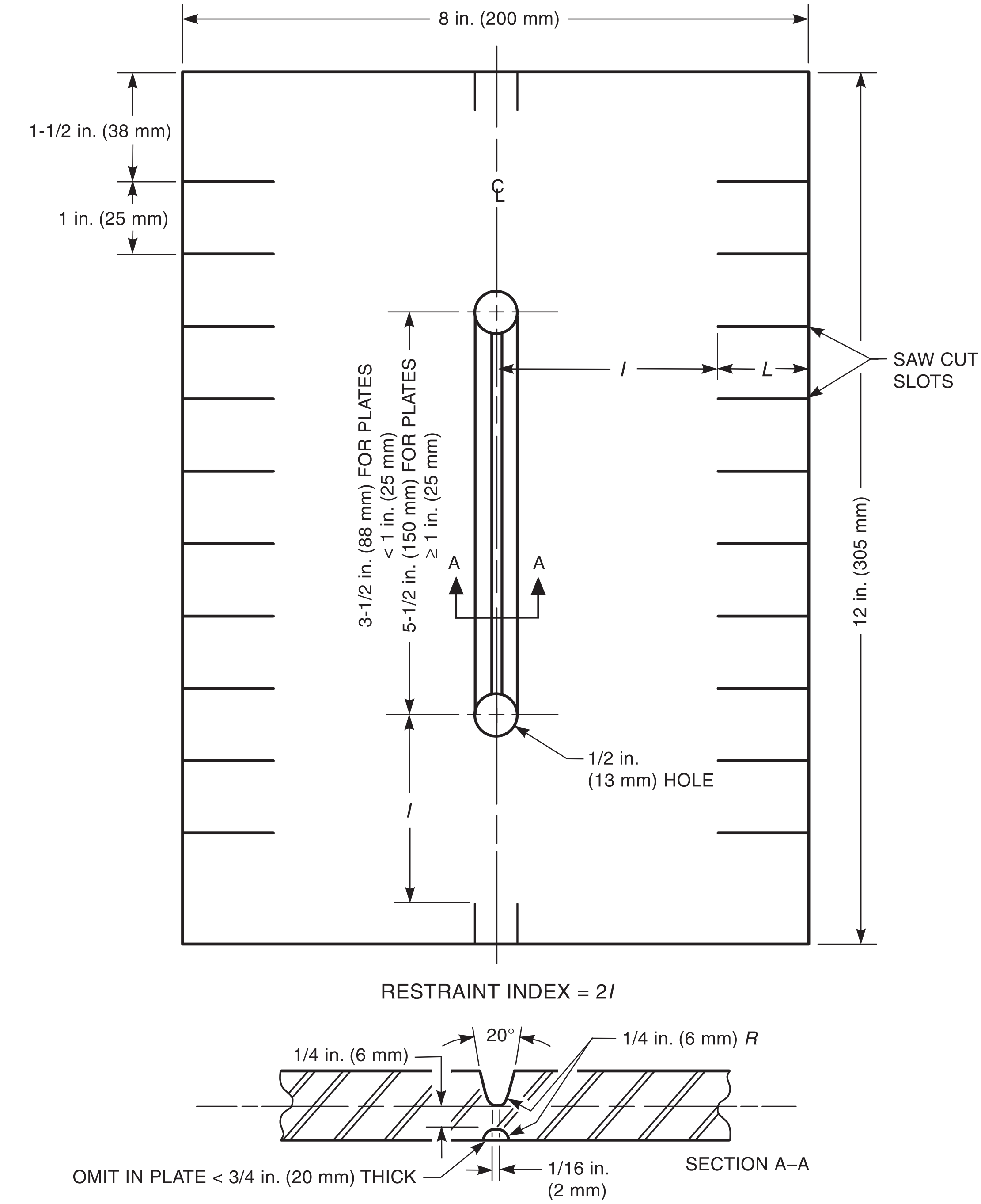
Controlled Thermal Severity Test. The controlled thermal severity (CTS) test[63] is used to evaluate susceptibility to cracking in carbon, carbon-manganese, and low-alloy steels. Although it is usually employed to examine the base metal, it can also be used to evaluate the effect of welding consumables, welding heat input, and heat treatments on the crack susceptibility of the heat-affected zone.

In this test, a plate is bolted and anchor welded to a second plate with two fillet (lap) welds, as shown in Figure 6.45. The fillet located at the plate edges is bithermal in that it has two paths of heat flow. The lap weld located near the middle of the bottom plate is trithermal as it has three paths of heat flow, thus inducing faster cooling. Further control of the cooling rate is possible by varying the plate thicknesses or using preheat.

When the specimen has cooled to ambient temperature, it is sectioned and inspected for cracks, and hardness is measured in the weld metal and the heat-

61. American Welding Society (AWS) Committee on Mechanical Testing of Welds, 1998, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0-98, Miami: American Welding Society.
62. See Reference 33.

63. See Reference 60.



Key:

l = Distance from the root of the saw-cut slots to the centerline of the specimen, in. (mm)
L = Length of the saw-cut slot, in. (mm)
R = Root radius, in. (mm)

Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds*, AWS B4.0M:2000, Miami: American Welding Society, Figure E13.

Figure 6.43—Lehigh Restraint Cracking Test Specimen

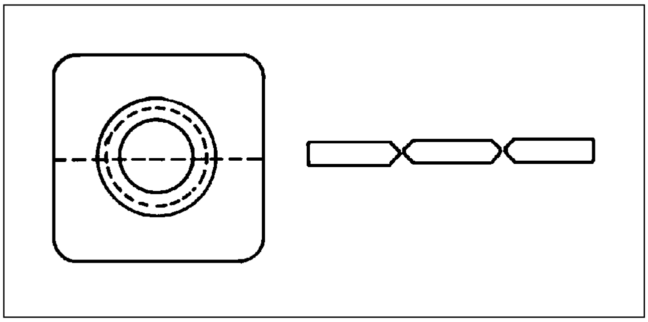


Figure 6.44—Circular Patch Test Specimen

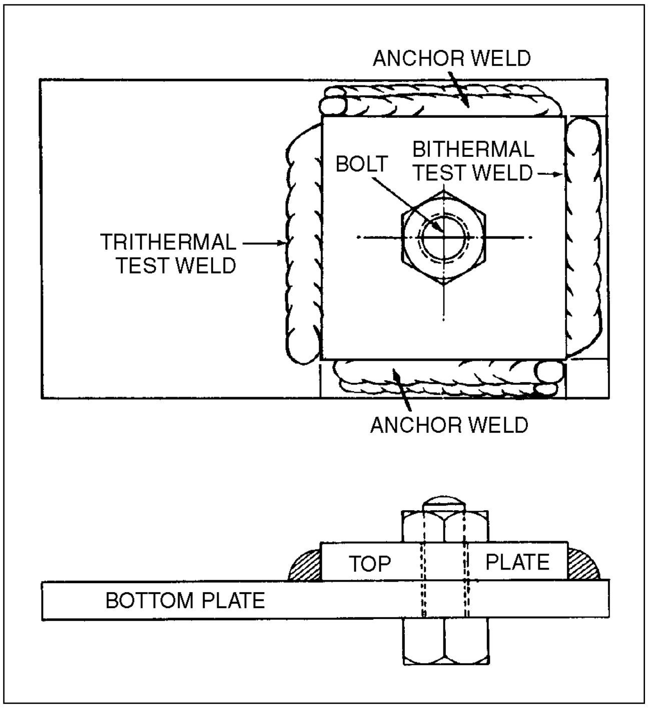


Figure 6.45—Controlled Thermal Severity (CTS) Test Specimen

affected zone. Details of the test procedure and sectioning locations are described in *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0-98[64] and AWS B4.0:2000.[65]

Cruciform Test. The cruciform test is used to measure the susceptibility of steel weldments to cracking. Applied primarily to fillet welds, this test provides valuable information on the effects of the composition of the base metal on the propensity to cracking.

The test specimen, shown in Figure 6.46, comprises three plates with ground surfaces tack welded at the ends to form a double T-joint. Four test fillet welds of the same size are deposited using the same welding parameters in succession in the order shown, allowing complete cooling between deposits. Careful fitup of the plates is necessary to obtain reproducibility. Cracking, which is most likely to occur in the third bead, is detected by cross-sectioning and visual or metallographic examination.

Implant Test. The implant test is used to determine susceptibility to cracking in the heat-affected zone of low-alloy steel weldments. It is often used in the selection of combinations of base metals and welding consumables to provide crack resistance.

In this test, a threaded rod welded into a hole in the test plate is subjected to a tensile load for 24 hours. Cracking is indicated when failure occurs at a low level of stress or a short period of time. An implant test fixture and a specimen are illustrated in Figure 6.47.

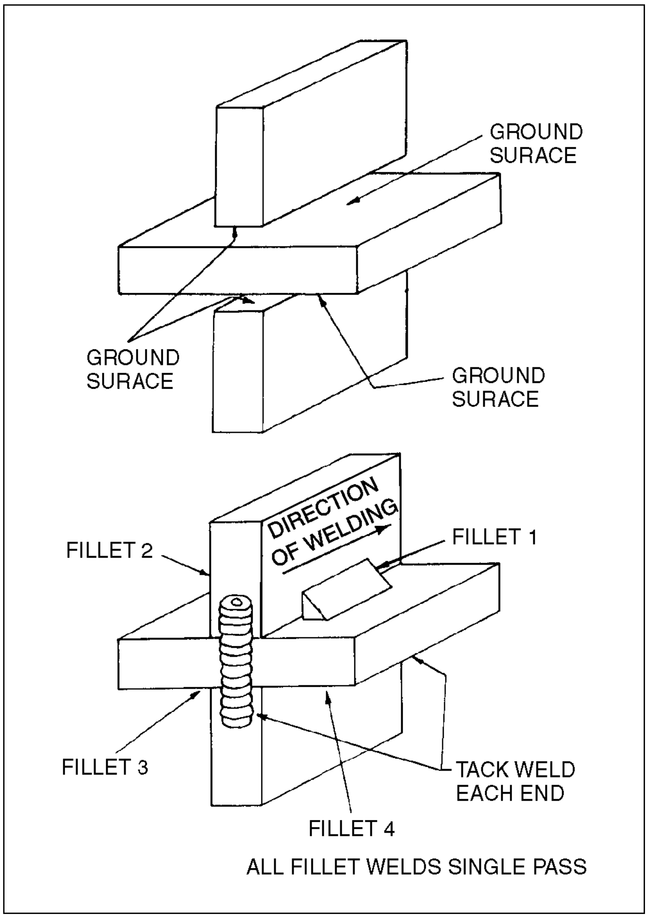
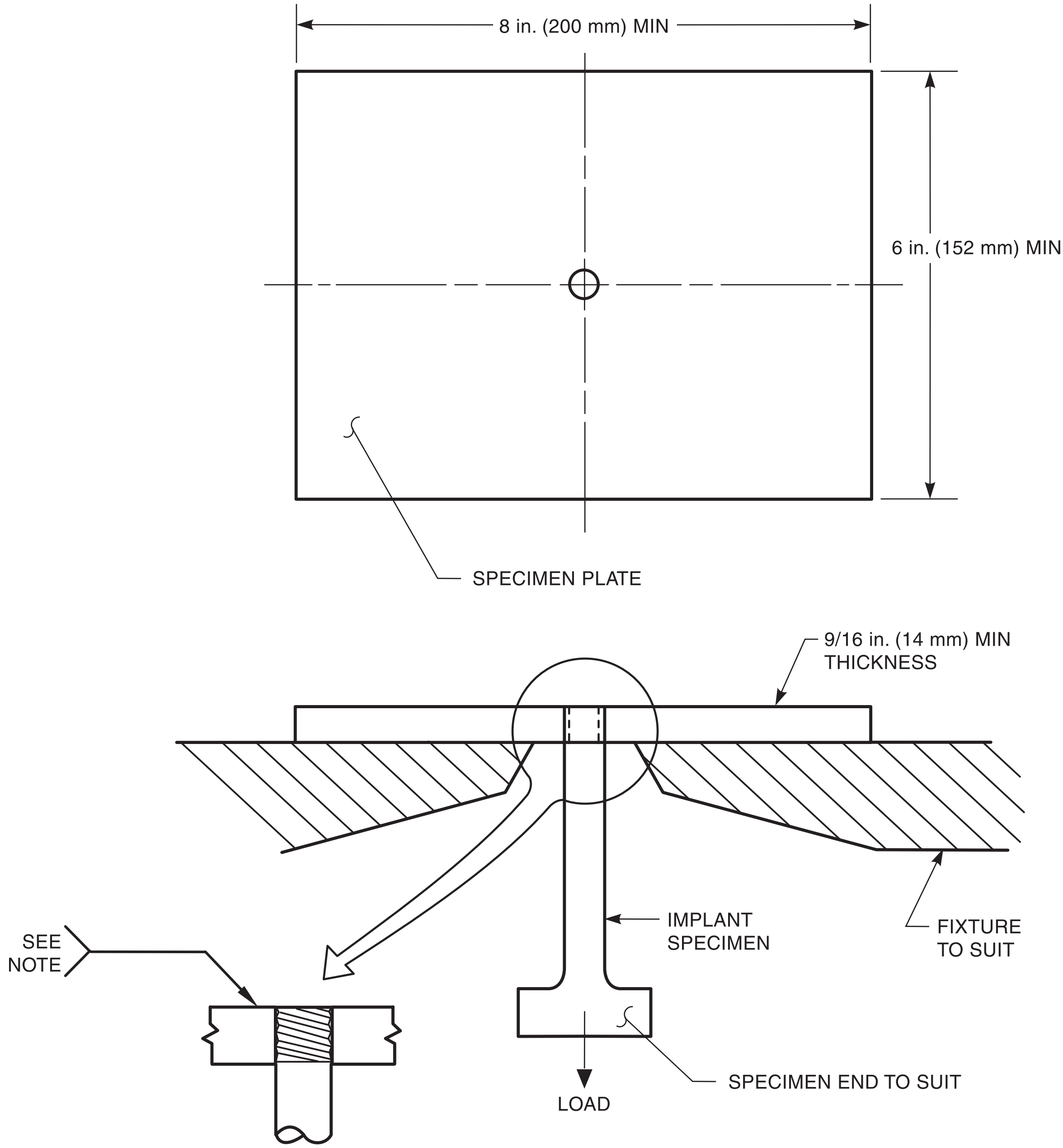


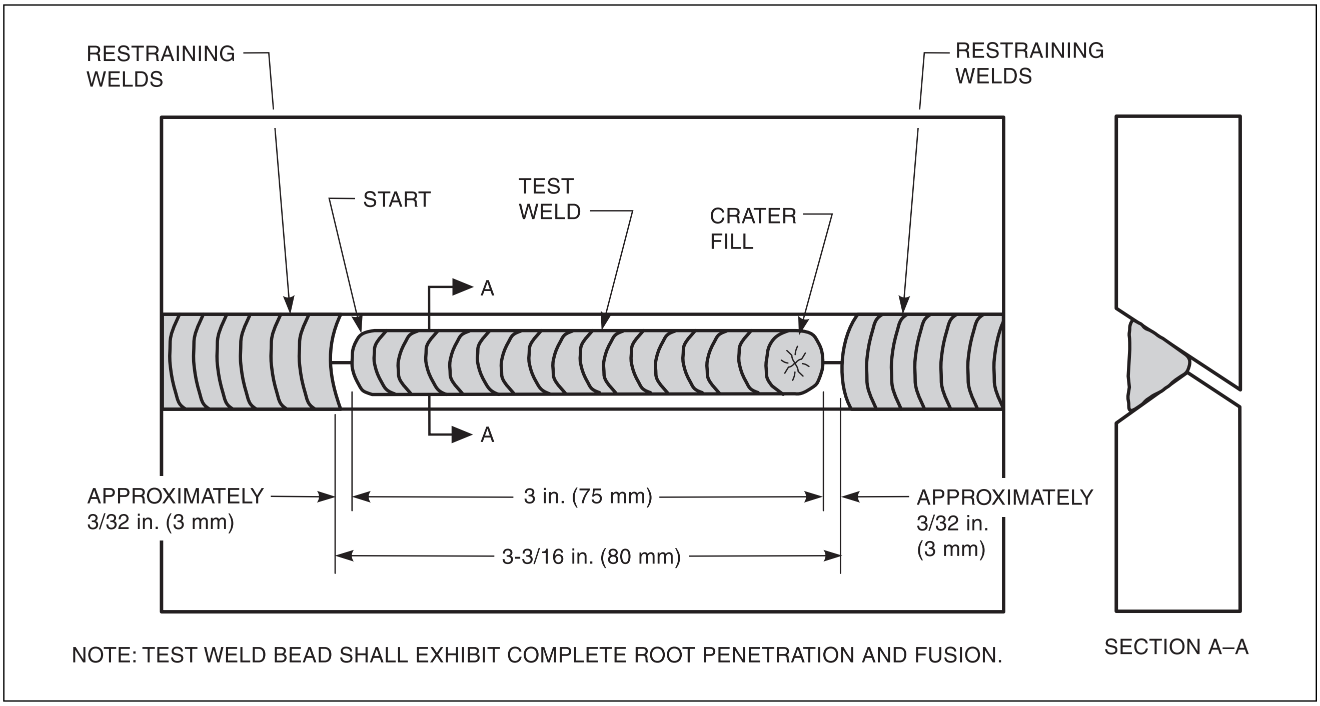
Figure 6.46—Cruciform Cracking Test Specimen

64. See Reference 61.
65. See Reference 33.



Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds*, AWS B4.0M:2000, Miami: American Welding Society, Figure E10.

Figure 6.47—Implant Test Specimen and Fixture



Source: Adapted from American Welding Society (AWS) Committee on Mechanical Testing of Welds, 2000, *Standard Methods for Mechanical Testing of Welds*, ANSI/AWS B4.0M:2000, Miami: American Welding Society, Figure E20.

Figure 6.48—Oblique Y-Groove Test Plate

Oblique Y-Groove Test. The oblique Y-groove test (Tekken test) is used to provide comparative data regarding the susceptibility of steel weldments to hydrogen-assisted and weld-metal-solidification cracking. This test involves the examination of a test weld made in a restrained, machined groove in three test assemblies. A single-pass weld is deposited in the flat position when the test assemblies have reached the desired preheat temperature. A typical test plate for mechanized welding is shown in Figure 6.48.

The test assembly is allowed to cool for at least 48 hours before it is inspected visually for the presence of surface cracking. In the absence of visible surface cracks, the welds are sectioned and examined microscopically.

CONCLUSION

Engineers design welded joints to meet the mechanical and physical properties required by the service application and environment. Such properties can include strength, ductility, toughness, fatigue resistance, and corrosion resistance, among others. The tests described in this chapter allow these properties to be determined for new materials and to be verified during production.

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66. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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CHAPTER 7

RESIDUAL STRESS AND DISTORTION

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Contents

CHAPTER 7

RESIDUAL STRESS AND DISTORTION

INTRODUCTION

The types of residual stress that occur in welds and their respective distribution patterns are quite complex. This chapter presents an analysis of stress in single- and multiple-pass welds and examines the various factors that interact to increase or decrease the magnitude of stress in welds. As distortion in weldments is an important factor in their serviceability, the procedures used to predict distortion are also discussed here. In the final section, the various procedures used to reduce or control residual stress and distortion in welds are examined in detail.

Since most information published on this subject concerns welds produced with the arc welding processes, the discussions presented in this chapter almost exclusively address residual stress and distortion in welds fabricated with these processes. A limited amount of information is presented on residual stress in spot welded joints in titanium 8Al-1Mo-1V alloy.

FUNDAMENTALS

A weldment undergoes localized heating during most welding processes; therefore, the temperature distribution in the weldment is not uniform, and structural and metallurgical changes take place as the welding progresses along a joint. Typically, the weld metal and the heat-affected zone immediately adjacent to the weld are at temperatures substantially above that of the unaffected base metal. As the weld pool solidifies and shrinks, it begins to exert stress on the surrounding weld metal and heat-affected zones. When the weld metal first solidifies, it is hot and relatively weak; thus, it exerts little stress. As the weld cools to ambient temperature, however, the stress in the weld area increases and eventually reaches the yield point of the base metal and the heat-affected zone.

When a weld is made progressively, the portions of the weld that have already solidified resist the shrinkage of later portions of the weld bead. Consequently, the portions welded first are strained in tension in a direction longitudinal to the weld, that is, down the length of the weld bead, as shown in Figure 7.1.

In the case of butt joints, little motion of the weld is permitted in the transverse direction because of the preparation of the weld joint and the stiffening effect of underlying passes. Because of shrinkage in the weld, transverse residual stress is also present, as shown in Figure 7.1. For fillet welds, the shrinkage stress is tensile along the length and across the face of the weld, as shown in Figure 7.2.

Residual stress in weldments can have two major effects. It can produce distortion or cause premature failure, or both. Distortion is caused when the heated weld region contracts nonuniformly, causing shrinkage in one part of a weld to exert eccentric forces on the weld cross section. The weldment strains elastically in response to this stress. Detectable distortion occurs as a result of this nonuniform strain.

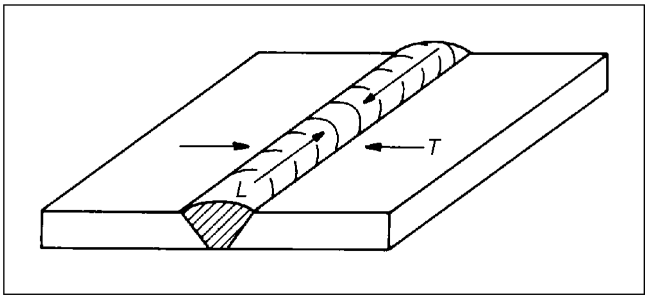


Figure 7.1—Longitudinal (*L*) and Transverse (*T*) Shrinkage Stress in a Butt Joint Weld

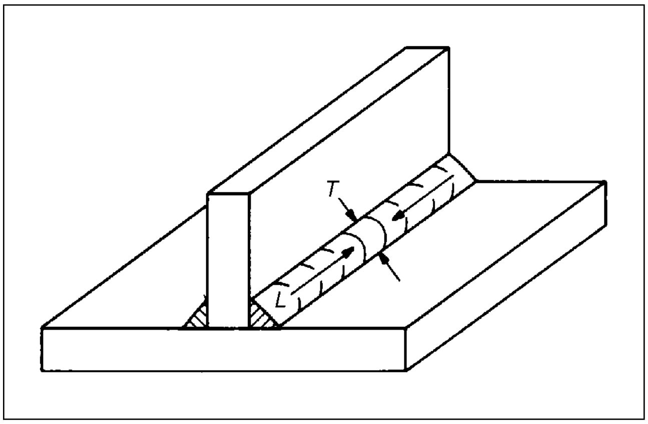


Figure 7.2—Longitudinal (*L*) and Transverse (*T*) Shrinkage Stress in a T-Joint

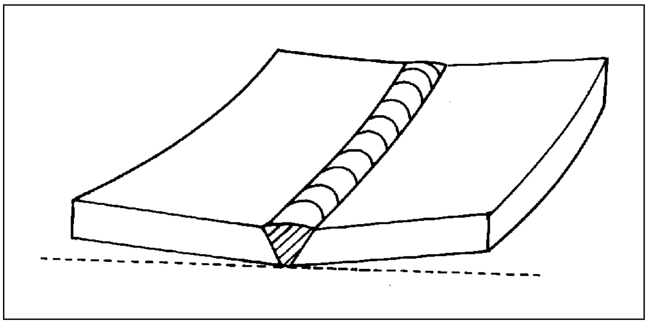


Figure 7.3—Schematic Representation of Distortion in a Butt Joint

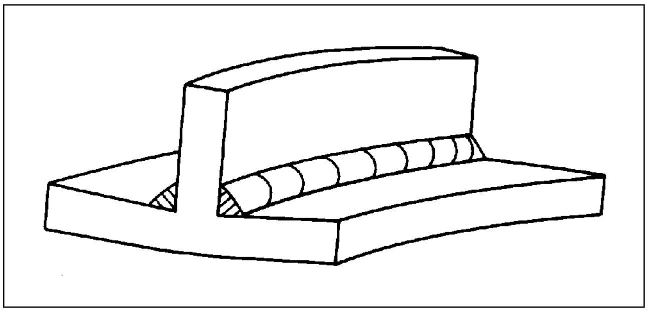


Figure 7.4—Schematic Representation of Distortion in a T-Joint

In butt joints in plate, this distortion may appear as both longitudinal and transverse shrinkage or contraction. It may also appear as angular change (rotation) when the face of the weld shrinks more than the root. Angular change produces transverse bending in the plates along the weld length. These effects are illustrated in Figure 7.3.

Distortion in fillet welds is similar to that which occurs in butt welds. Transverse and longitudinal shrinkage and angular distortion result from the unbalanced nature of the stress present in these welds. As fillet welds are often used in combination with other welds in welded structures, the specific resulting distortion may be very complex. This behavior is shown in Figure 7.4.

Distortion can be controlled by means of a number of techniques. The most commonly used techniques control the geometry of the welded joint either before or during welding. These techniques include (1) prepositioning the workpieces prior to welding so that the subsequent weld distortion leaves them in the desired final geometry and (2) restraining the workpieces so they cannot distort during welding. Designing and welding the joint so that weld deposits are balanced on each side of the weld centerline is another useful technique. The selection of the welding process to be used as well as the weld sequence can also influence distortion and residual stress.

Residual stress and distortion affect the fracture behavior of materials by contributing to buckling and brittle fractures at low applied-stress levels. When residual stress and the accompanying distortion are present, buckling may occur at lower compressive loads than would otherwise be predicted. In tension, residual stress may lead to high local stress in weld regions of low notch toughness. This local stress may initiate brittle cracks that are propagated by any low overall stress that is present. In addition, residual stress may contribute to fatigue or corrosion failures.

Residual stress may be reduced or eliminated by both thermal and mechanical means. During thermal stress relief, the weldment is heated to a temperature at which the yield point of the metal is low enough for plastic flow to occur and thus allow relaxation of stress. The mechanical properties of the weldment are usually affected by thermal stress relief. For example, the brittle fracture resistance of many steel weldments is often improved by thermal stress relief because residual stress in the weld is reduced and the heat-affected zones are tempered. The toughness of the heat-affected zones is improved by this procedure. Mechanical stress-relief treatments also reduce residual stress, but they do not significantly change the microstructure or hardness of the weld or heat-affected zone.

Improving the reliability of welded metal structures is of the utmost importance. During the design phase, engineers must consider the effects of residual stress and distortion, the presence of discontinuities, the mechanical properties of the weldment, the requirements for nondestructive examination, and the total fabrication costs.

The reduction of residual stress and distortion can be achieved by means of a number of techniques, including the following:

1. Choosing appropriate processes, procedures, welding sequence, and fixturing;
2. Selecting optimal methods for stress relief and the removal of distortions; and
3. Using design details and materials to minimize the effects of residual stress and distortion.

NATURE AND CAUSES OF RESIDUAL STRESS

The term *residual stress* refers to the stress that exists in a weldment after all external loads have been removed. Various terms have been used to describe residual stress. These include *internal stress*, *initial stress*, *inherent stress*, *reaction stress*, and *locked-in stress*. However, the residual stress that occurs when a structure is subjected to nonuniform temperature change is usually termed *thermal stress*.

Residual stress develops in metal structures during the various manufacturing stages for many reasons. During casting or mechanical working (e.g., rolling, forging, or bending), stress may be produced in structural components such as plates, bars, and sections. It may also occur during fabrication as a result of welding, brazing, and thermal cutting operations.

Heat treatments applied at various stages of manufacture can also affect residual stress. For example, quenching from elevated temperature can cause residual stress, whereas stress-relieving heat treatments can reduce it.

MACROSCOPIC AND MICROSCOPIC RESIDUAL STRESS

The portions of a metal structure in which residual stress can be found vary greatly, ranging from large sections of the structure to areas on the atomic scale. Examples of macroscopic residual stress are presented in Figure 7.5. When a structure is heated by solar radiation on one side, thermal distortions and thermal stress are produced in the structure, as shown in Figure 7.5(A). The residual stress produced by welding is illustrated Figure 7.5(B). In this figure, it can be observed that the stress is confined to areas near the weld. Figure 7.5(C) depicts residual stress produced by grinding. In this case, the stress is highly localized in a thin layer near the surface.

Residual stress also occurs on a microscopic scale. For example, residual stress is produced in steels during martensitic transformation.[1] As this process takes place at a low temperature, it results in the expansion of the metal.

FORMATION OF RESIDUAL STRESS

The different types of residual stress are classified according to the mechanisms that produce them, namely, structural mismatching and the uneven distribution of nonelastic strains, including plastic and thermal strains.

Residual Stress Resulting from Structural Mismatch

Figure 7.6 illustrates a simple case in which residual stresses are produced when bars of different lengths are forcibly connected. Figure 7.6(A) shows the system in the free state. An opening exists between the two portions of Bar Q, which is slightly shorter than Bars P and P′. When these two portions are forcibly connected as shown in Figure 7.6(B), tensile residual stresses are produced in Bar Q, while compressive residual stresses are produced in Bars P and P′. If the cross-sectional areas of P, P′, and Q are equal, the absolute values of the stresses in Q are twice those present in P and P′. The entire system becomes slightly shorter after the two portions of bar Q are forcibly connected.

Satoh, Matsui, and Machida[2] used an experimental system similar to that shown in Figure 7.6 to study the mechanisms leading to the formation of residual stresses. Figure 7.7 shows the experimental system used. Two round bars were used to restrain the movement of the round bar specimen shown in the middle. The round bar specimen, which was set in the rigid frame, was subjected to a thermal cycle simulating the welding thermal cycle. The specimen was first heated using a high-frequency induction device. The specimen was then naturally air-cooled or control-cooled using a stream of argon gas. A load cell attached to the specimen was used to measure thermal stresses developed in the specimen. The thermal cycle was measured by means of thermocouples.

1. Martensitic transformation in steel is described in Chapter 4 of this volume.
2. Satoh, K., S. Matsui, and T. Machida, 1966, Thermal Stresses Developed in High-Strength Steels Subjected to Thermal Cycles Simulating Weld Heat-Affected Zone, *Journal of Japan Welding Society* 35(9): 780–788 (in Japanese).

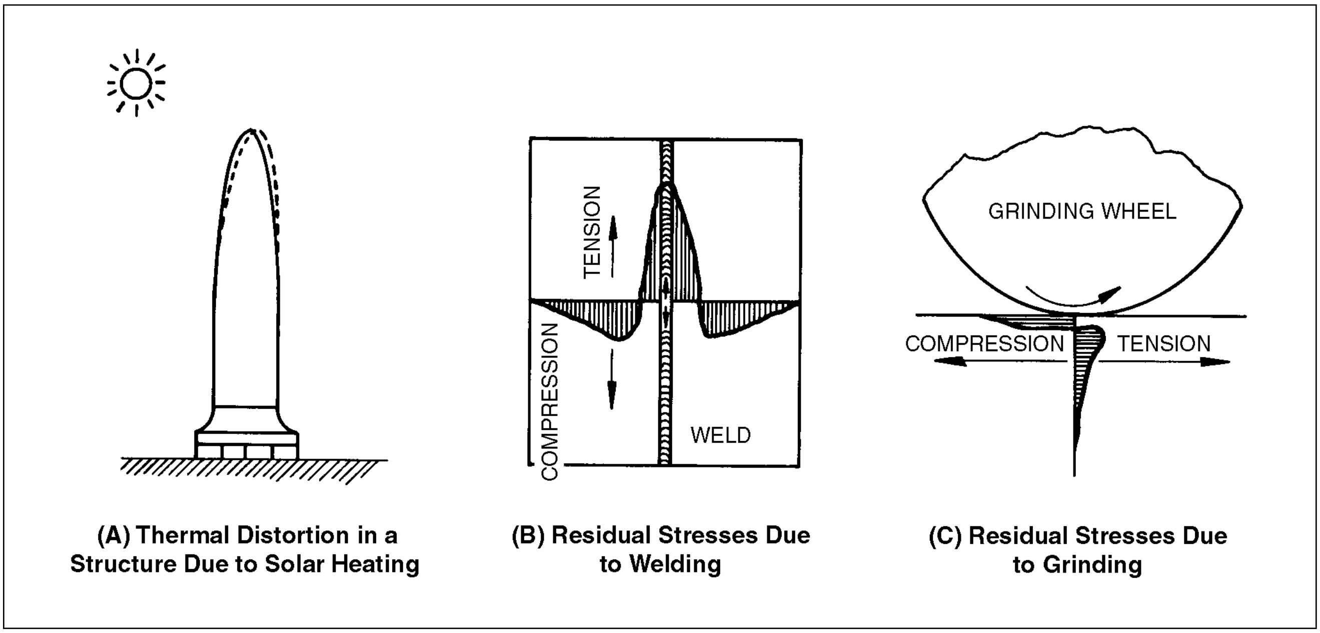


Figure 7.5—Macroscopic Residual Stresses on Various Scales: (A) Thermal Distortion Due to Solar Heating; (B) Residual Stress Due to Welding; and (C) Residual Stress Due to Grinding

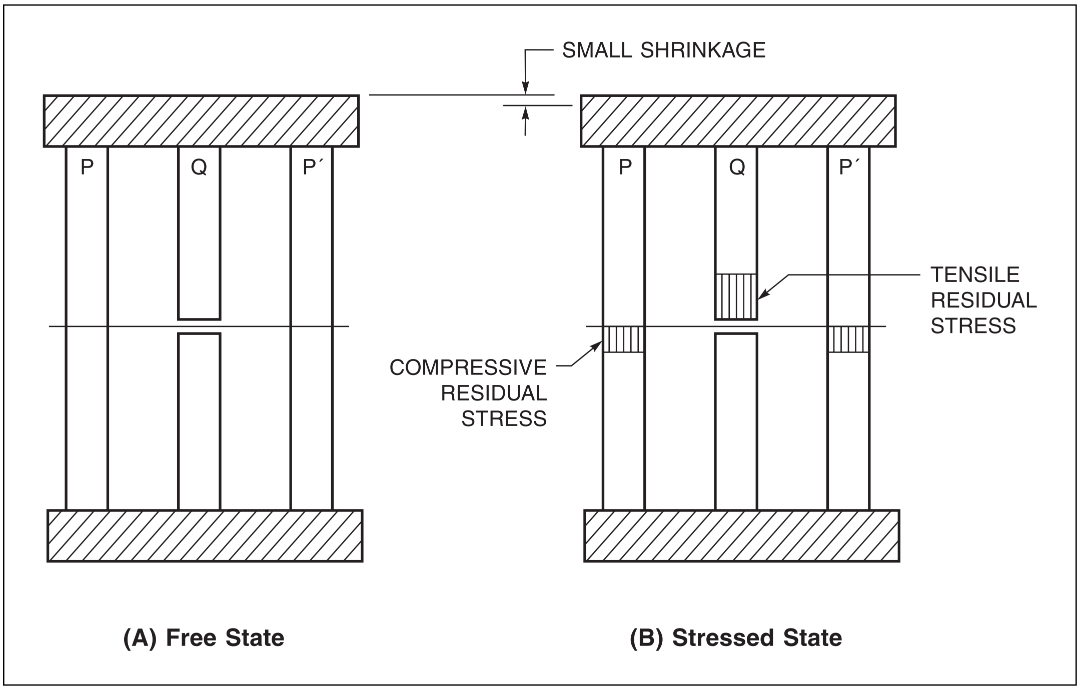
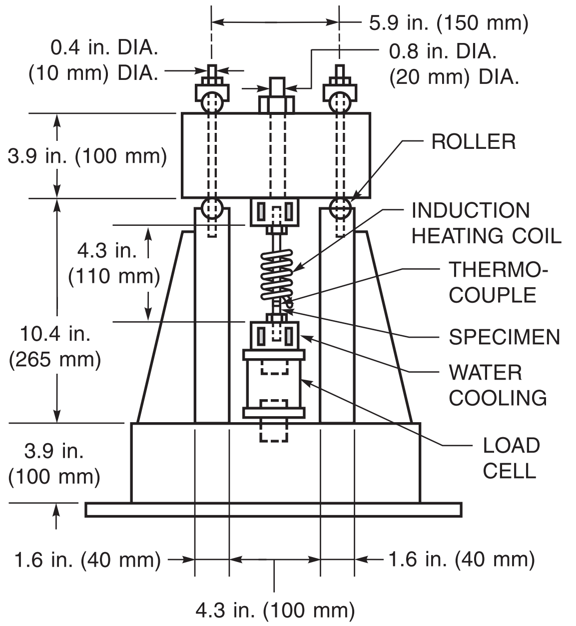


Figure 7.6—Residual Stress Produced When Bars of Different Lengths Are Forcibly Connected: (A) Free State and (B) Stressed State



Source: Adapted from Satoh, K., S. Matsui, and T. Machida, 1966, Thermal Stresses Developed in High-Strength Steels Subjected to Thermal Cycles Simulating Weld Heat-Affected Zone, *Journal of Japan Welding Society* 35(9): 780–788 (in Japanese).

Figure 7.7—Experimental System Used to Investigate the Formation of Residual Stress

Experiments were performed on two types of steel: (1) a low-carbon steel and (2) a Japanese HT-70 steel, which is very similar to the U.S. HY-80 steel. The HT-70 steel is a low-alloy, high-strength steel with the minimum tensile strength of 99.6 ksi (70 kg/mm^2 or 686 MPa), while the HY-80 steel has the minimum yield strength of 80 ksi (56.2 kg/mm^2 or 552 MPa). The latter is widely used for the pressurized hulls of U.S. submarines.

The experimental results obtained in the investigation of the low-carbon steel and HY-80 steel specimens are shown in Figures 7.8(A) and Figure 7.8(B), respectively. Figure 7.8(A) illustrates the changes in stresses that occurred in the low-carbon steel bar during the heating and cooling cycles. While the middle bar specimen was being heated, compressive stresses were produced in the specimen because the expansion of the heated middle bar was restrained by the rigid frame.

As the temperature of the middle bar specimen increased, the compressive stresses in the bar increased, as shown by Line AB. As the temperature of the middle bar specimen reached approximately 600°F (300°C), the stress reached the yield stress of 34 ksi (230 MPa), as indicated by Point B.

As the temperature was further increased beyond Point B, the compressive stresses in the middle bar specimen were limited to the yield stress, which decreased with temperature, as shown by Curve BC. When the temperature of the middle bar specimen approximated 1380°F (750°C), the compressive stress in the middle bar became almost zero. The heating was terminated at Point D when the temperature reached 2570°F (1410°C).

As the temperature of the middle bar specimen fell below 2570°F (1410°C), the bar started to shrink, but the tensile stresses remained very low until the temperature decreased to approximately 1100°F (600°C), indicated by Point E. The stress increased rather rapidly when the temperature decreased below 1100°F (600°C). The stress reached the yield stress in tension at 400°F (204°C), as indicated by Point F.

As the temperature decreased further, the magnitude of the stress increased only slightly to the final value of approximately 60 ksi (406 MPa). Line X shows the manner in which the stresses increased during air cooling, while Line Y shows how the stresses increased during rapid cooling. It can be observed that the difference in the cooling method had little effect on the amount of residual stresses that remained in the specimen after the heating and cooling cycle.

Figure 7.8(B) shows the results of similar experiments performed on the high-strength steel, HY-80. Although the results shown in Figure 7.8(B) are similar to those presented in Figure 7.8(A), several differences can be noted. Regarding Point B, at which the compressive stress reached the maximum, the HY-80 specimen showed the maximum stress of 51 ksi (406 MPa) as compared to 34 ksi (234 MPa) for the low-carbon steel specimen. This difference is due to the differing strengths of these materials at elevated temperatures. A unique feature of the HY-80 specimen is the significant drop in tensile residual stresses during the cooling cycle, as indicated by Points E and F. This is caused by the expansion of the material during metallurgical transformation, including the formation of martensitic structures on cooling.

Although it is commonly believed that the maximum tensile residual stresses in many welds are as high as the yield strength of the base metal used, investigations have shown that the maximum values of residual stresses in welds made in some high-strength steels are not as high as the yield strengths of the material.[3] Figure 7.8(B) explains how and why residual stresses in welds made in a high-strength steel can be lower than the yield stress of the base plate.

3. Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion, and Their Consequences*, New York: Pergamon Press.

LIVE GRAPH
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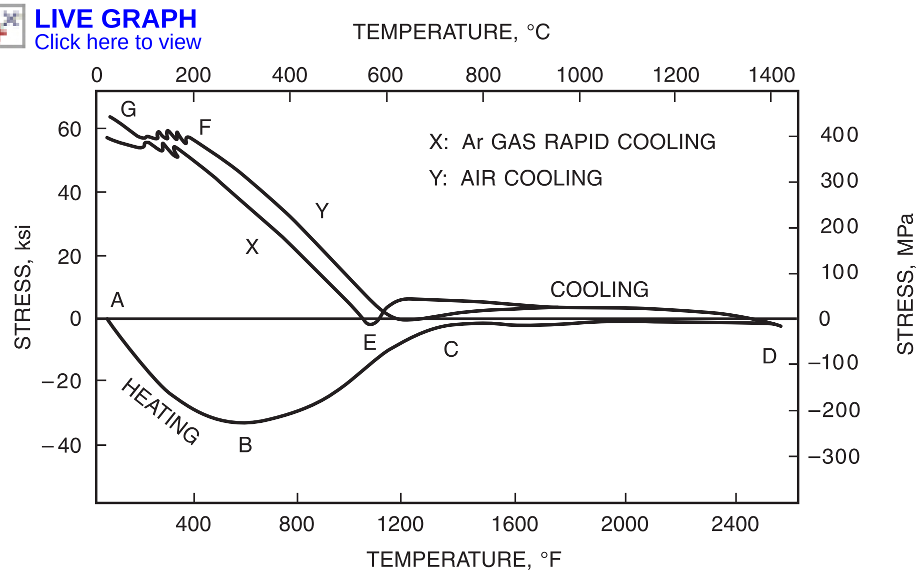

(A) Low-Carbon Steel Specimens

LIVE GRAPH
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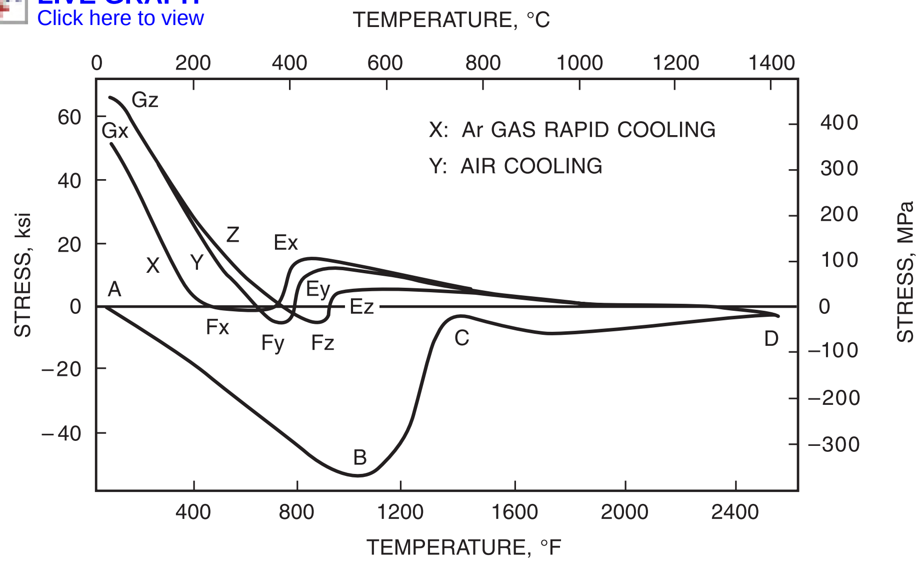


(B) HY-80 Steel Specimens

Source: Satoh, K., S. Matsui, and T. Machida, 1966, Thermal Stresses Developed in High-Strength Steels Subjected to Thermal Cycles Simulating Weld Heat-Affected Zone, *Journal of Japan Welding Society* 35(9): 780–788 (in Japanese).

Figure 7.8—Experimental Results Indicating Changes in Stress during the Heating and Cooling Cycles

Residual Stress Produced by Unevenly Distributed Nonelastic Strain

When a metal is heated uniformly, it expands uniformly, yielding no thermal stress. On the other hand, if the metal is heated unevenly, thermal stresses and strains develop.[4] Residual stress may also be produced when the object is deformed plastically.

The fundamental relationships necessary for the creation of a plane-stress/residual-stress field ($\sigma_z = 0$) are presented below:[5]

1. Strains consist of both elastic strain and plastic strain:

$$\varepsilon_x = \varepsilon'_x + \varepsilon''_x$$

$$\varepsilon_x = \varepsilon'_y + \varepsilon''_y$$

$$\gamma_{xy} = \gamma'_{xy} + \gamma''_{xy} \tag{7.1}$$

where

$\varepsilon_x, \varepsilon_y$, and γ_{xy} = Components of the total strain,

$\varepsilon'_x, \varepsilon'_y$, and γ'_{xy} = Components of the elastic strain, and

$\varepsilon''_x, \varepsilon''_y$, and γ''_{xy} = Components of the plastic strain.

2. A Hooke's law relationship exists between the stress and the elastic strain; thus,

$$\varepsilon'_x = \frac{1}{E}\left(\sigma_x - \nu\sigma_y\right)$$

$$\varepsilon'_y = \frac{1}{E}\left(\sigma_y - \nu\sigma_x\right)$$

$$\gamma_{xy} = \frac{1}{G}\tau_{xy} \tag{7.2}$$

where

ε'_x = Component of the elastic strain in the x-direction;
E = Modulus of elasticity;
σ_x = Normal stress in the x-direction;
ν = Poisson's ratio;
σ_y = Normal stress in the y-direction;
ε'_y = Component of elastic strain in the y-direction;
γ_{xy} = Shear strain on the x-y plane;
G = Shear modulus, which equals $E/2(1 + \nu)$; and
τ_{xy} = Shear stress on the x-y plane.

3. The stress must satisfy the equilibrium conditions:

$$\frac{\partial\sigma_x}{\partial x} + \frac{\partial\tau_{xy}}{\partial y} = 0$$

$$\frac{\partial\tau_{xy}}{\partial x} + \frac{\partial\sigma_y}{\partial y} = 0 \tag{7.3}$$

where

σ_x = Normal stress in the x-direction;
x = Distance in the x-direction from the origin;
τ_{xy} = Shear stress on the x-y plane;
σ_y = Normal stress in the y-direction; and
y = Distance in the y-direction from the origin.

4. The total strain must satisfy the condition of compatibility:

$$\left[\frac{\partial^2\varepsilon'_x}{\partial y^2} + \frac{\partial^2\varepsilon'_y}{\partial x^2} - \frac{\partial^2\gamma'_{xy}}{\partial x\partial y}\right] + \left[\frac{\partial^2\varepsilon''_x}{\partial y^2} + \frac{\partial\varepsilon''_y}{\partial x^2} - \frac{\partial^2\gamma''_{xy}}{\partial x\partial y}\right] = 0 \tag{7.4}$$

where

ε'_x = Component of the elastic strain in the x-direction;
y = Distance in the y-direction form the origin;
ε'_y = Normal strain in the y-direction;
x = Distance in the x-direction from the origin;
γ'_{xy} = Shear strain in the x-y plane;
ε'_x = Normal strain in the x-direction;
ε''_y = Normal strain in the y-direction; and
γ''_{xy} = Shear strain on the x-y plane.

Equations (7.3) and (7.4) indicate that residual stress exists when the value of R, which denotes incompatibil-

4. Thermal strains are related to the coefficient of linear thermal expansion and the change in temperature as follows:

$$\varepsilon''_x = \varepsilon''_y = \alpha\Delta T$$

$$\gamma''_{xy} = 0$$

where ε''_x = normal strain in the x-direction; ε''_y = normal strain in the y-direction; α = the coefficient of linear thermal expansion; ΔT = the change of temperature from the initial temperature; and γ''_{xy} = shear strain on the x-y plane.

5. In a typical three-dimensional stress field ($\sigma_z \neq 0$), six stress components exist: σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, and τ_{zx}.

ity,[6] is not zero. The term R is determined by the plastic strain using the following equation:

$$R = -\left[\frac{\partial^2 \varepsilon''_x}{\partial y^2} + \frac{\partial \varepsilon''_y}{\partial x^2} - \frac{\partial \gamma''_{xy}}{\partial x \partial y}\right] \quad (7.5)$$

where

R = Incompatibility, in.$^{-2}$ (mm^{-2}).

Thus, incompatibility, R, can be considered the cause of residual stress.

Several equations have been proposed to calculate stress components σ_x, σ_y, and τ_{xy} for the given values of plastic strain, ε''_x, ε''_y, and γ''_{xy}. The conclusions obtained from these mathematical analyses include the following:[7]

1. Residual stress in a body cannot be determined by measuring the stress change that takes place when external load is applied to the member, and
2. Residual stress components σ_x, σ_y, and τ_{xy} can be calculated from Equation (7.2) when the elastic strain components ε'_x, ε'_y, and γ'_{xy} are determined. However, the plastic strain components, ε''_x, ε''_y, and γ''_{xy}, which cause the residual stress, cannot be determined without knowing the history of the formation of the residual stress.

Equilibrium Condition of Residual Stress

Since residual stress is not a result of external force, it cannot produce a resultant force or a resultant moment. This concept is expressed mathematically as shown in the following:

$$\int \sigma dA = 0 \text{ on any plane} \quad (7.6)$$

where

σ = Stress, and
dA = Infinitesimal area.

and

$$\int \sigma z dA = 0 \quad (7.7)$$

where

σ = Stress,
z = Distance from a reference point, and
dA = Infinitesimal area.

THERMAL STRESS AND THE RESULTING RESIDUAL STRESS

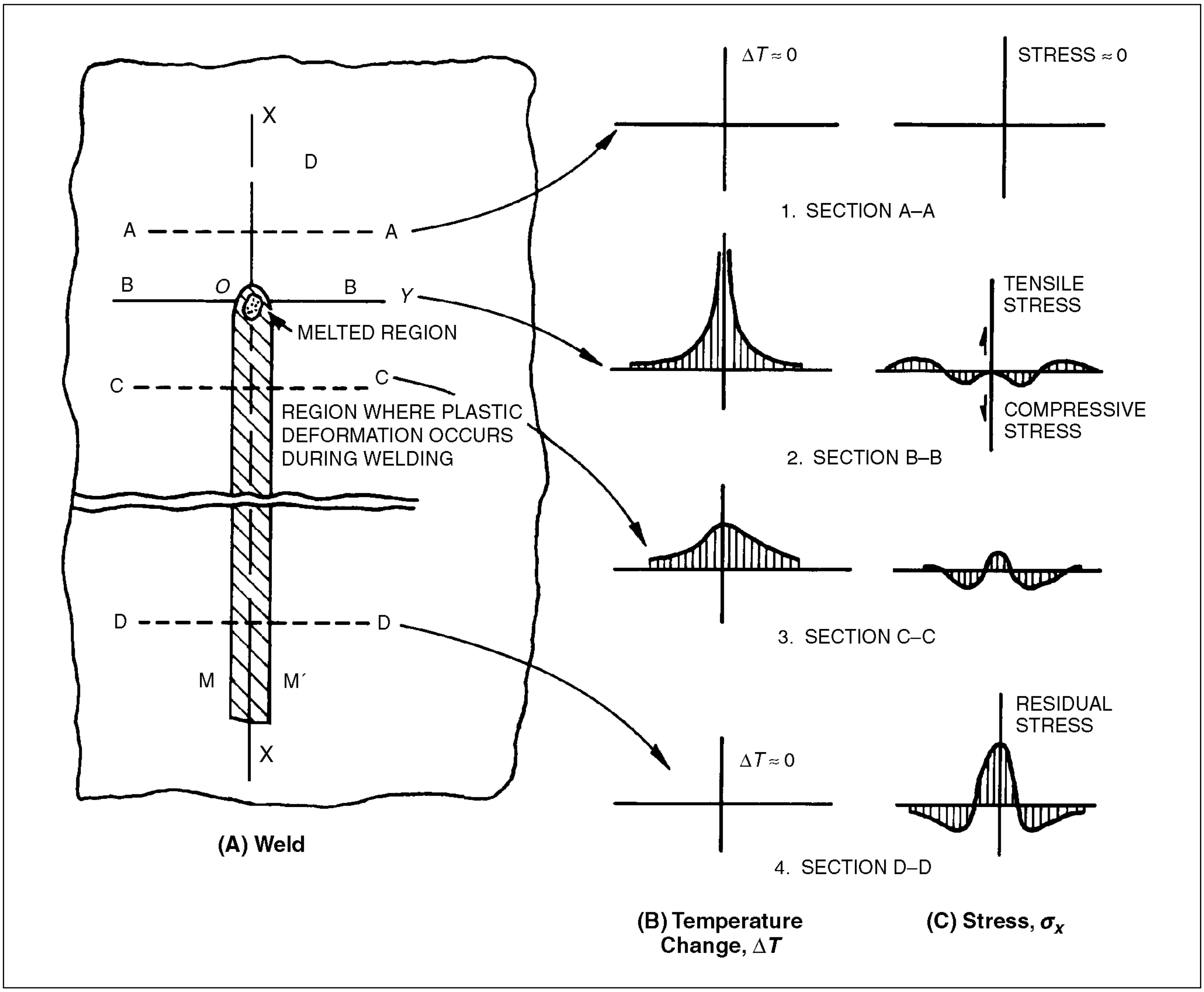
The changes in temperature and stress that occur during welding are shown schematically in Figure 7.9. In this application, a bead-on-plate weld is being deposited along Line X-X. The welding arc, which is moving at velocity v, is presently located at Point O, as shown in Figure 7.9(A).

Figure 7.9(B) shows the temperature distributions transverse to Line X–X at locations A, B, C, and D. Across Section A–A, which is ahead of the welding arc, the temperature change, ΔT, due to welding is essentially zero. However, the temperature distribution is very steep across Section B-B, which crosses the welding arc. Along Section C–C, at some distance behind the welding arc, the temperature distribution is much less severe. Farther away from the welding arc, the temperature across Section D–D has returned to a uniform distribution.

The distribution of the normal stress in the x-direction, σ_x, at Sections A–A, B–B, C–C, and D–D is illustrated in Figure 7.9(C). The normal stress in the y-direction, σ_y, and the shear stress, τ_{xy}, also exist in a two-dimensional stress field, though these are not shown in Figure 7.9.

At Section A–A, the thermal stress due to welding is almost zero. Stress is nearly nonexistent in the regions below the weld pool at Section B–B because the hot metal cannot support a load. Stress in the heat-affected zones on both sides of the weld pool is compressive because the expansion of these areas is restrained by surrounding metal that is at lower temperatures. The temperature of the metal near the arc is high, and the resulting yield strength is low. The compressive stress will reach yield level at the temperature of the metal. The magnitude of the compressive stress reaches a maximum with increasing distance from the weld (i.e., with decreasing temperature). At some distance away from the weld pool, the tensile stress must balance with the compressive stress in the heat-affected zones due to equilibrium conditions. This balance satisfies Equation (7.6). The instantaneous stress distribution along Section B–B is shown in Figure 7.9(C)2.

6. Moriguchi, S., 1956, *Theory of Two-Dimensional Elasticity*, in *Modern Applied Mechanics Series*, Tokyo: Iwanami Publishing; Moriguchi, S., 1948a, Fundamental Theory of Dislocation in an Elastic Body, *Oyo Sugaku Rikigaku [Applied Mathematics and Mechanics]* 1(4): 87–90; Moriguchi, S., 1948b, Fundamental Theory of Dislocation in an Elastic Body, *Oyo Sugaku Rikigaku [Applied Mathematics and Mechanics]* 1(2): 29–36.
7. See Reference 3.



Courtesy of the Welding Research Council (adapted)

Figure 7.9—Distribution of Temperature, ΔT, and Stress, σ_x, During the Production of a Bead-on-Plate Weld

At Section C–C, the weld metal and heat-affected zones have cooled. As they attempt to shrink, tensile stress is induced in the weld metal. This tensile stress is balanced by compressive stress in the cooler base metal. The stress distribution is illustrated in Figure 7.9(C)3.

The final condition of residual stress for the weld is shown in Section D–D. Along this section, high tensile stress exists in the weld and heat-affected zones, while compressive stress exists in the base metal away from the weld. The final stress distribution of the member is shown in Figure 7.8(C)4.

Based on this examination of a bead-on-plate weld, it is obvious that thermal stress during welding is produced by a complex series of mechanisms that involve plastic deformation at a wide range of temperatures, ranging from ambient temperature to melting temperature. Because of the difficulty in analyzing plastic deformation, especially at elevated temperatures, mathematical analyses are presently limited to very simple cases.

Metal Movement during Welding

During welding, the weldment undergoes shrinkage and deformation. This transient deformation, or metal movement, is most evident when the weld line is away

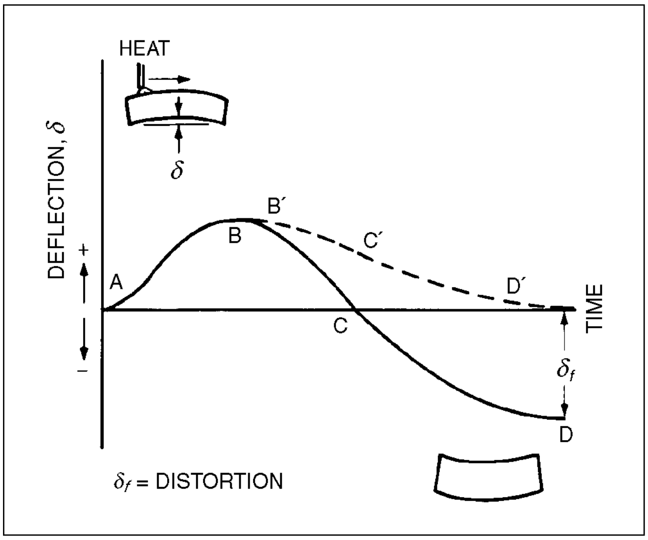


Figure 7.10—Time Change of the Center Deflection, δ, of a Metal Bar under the Influence of a Longitudinal Moving Heat Source

from the neutral axis of the weldment, causing a bending moment.[8] Figure 7.10 depicts the deflection of a rectangular metal bar when a longitudinal edge is heated by a moving welding arc or an oxyfuel gas heating torch. The metal near the heat source (the upper regions of the bar) is heated to higher temperatures than the metal farther away from the heat source (the lower regions of the bar). The hotter metal expands, and the bar first deforms, as shown by Curve AB.

If all the material remained completely elastic during the entire thermal cycle, any thermal stress produced during the heating-and-cooling cycle would disappear when the bar returns to ambient temperature. The deflection of the bar would then follow Curve AB′C′D′, and the bar would be straight after the thermal cycle. In most cases, however, plastic strains are produced by the thermal cycle, and after cooling, the bar contains residual stress. The transient deformation of the bar during the heating and cooling cycle is shown by Curve ABCD. After the bar cools to the ambient temperature, a final deformation, δ_f, remains. This deformation is also termed *distortion*.

It is interesting to note that the metal movement during welding and the distortion that occurs after welding are in opposite directions and generally of the same order of magnitude.

RESIDUAL STRESS AND REACTION STRESS IN WELDMENTS

The types of residual stress that occur during the fabrication of welded structures are classified as (1) residual welding stress that is produced in the welding of unrestrained members and (2) reaction stress that is caused by external restraint.

Typical distributions of longitudinal and transverse residual stress in a single-pass weld in a butt joint are shown in Figure 7.11. The stresses of concern are those longitudinal to the welding direction, designated σ_x, and those transverse to it, designated σ_y, as shown in Figure 7.11(A).

Figure 7.11(B) illustrates the distribution of the longitudinal residual stress, σ_x. Residual stress of a high magnitude in tension is produced in the region near the weld. It decreases rapidly to zero over a distance several times the width of the weld metal. Farther away, the residual stress is compressive in nature. The distribution of these stresses is characterized by two variables—the maximum stress in weld region, σ_m, and the half width of the tensile zone of residual stress, f. In weldments made in low-carbon steel, the maximum residual stress, σ_m, is usually as high as the yield strength of the weld metal. The distribution of the longitudinal residual stress is shown in Figure 7.11(B), and can be approximated by the following equation:[9]

$$\sigma_x(y) = \sigma_m\left[1-\left(\frac{y}{f}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{y}{f}\right)^2\right] \qquad (7.8)$$

where

σ_x = Longitudinal residual stress, psi (MPa);
y = Lateral distance from the weld centerline, in. (mm);
σ_m = Maximum tensile residual stress along the centerline of the weld, psi (MPa); and
f = Half-width of the tensile residual stress zone, in. (mm).

The distribution of the transverse residual stress, σ_y, along the length of the weld is represented by Curve 1 in Figure 7.11(C). Tensile stress of a relatively low magnitude is produced in the middle section of the joint,

8. Masubuchi, K., 1983, The Need for Analytical/Experimental Orchestrated Approaches to Solve Residual Stress Problems in Real Structures, in *Nondestructive Methods for Material Property Determination,* C. O. Ruud and R. E. Green, eds., New York: Plenum Press.

9. Uhlig, H. H., 1963, *Corrosion and Corrosion Control and Introduction to Corrosion Science and Engineering,* New York: John Wiley and Sons.

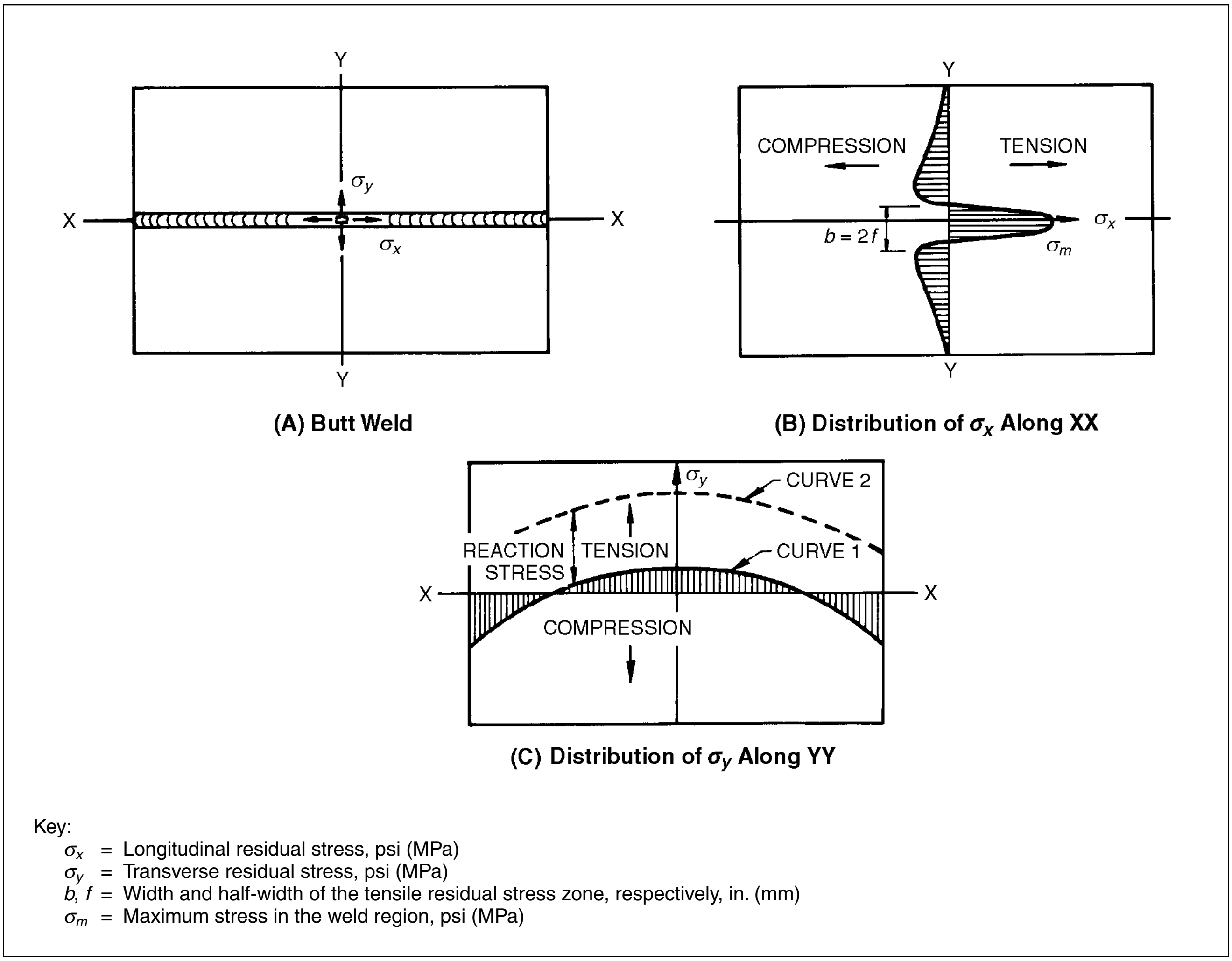


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Figure 7.11—Typical Distribution of Longitudinal (σ_X) and Transverse Residual Stress (σ_Y) in a Butt Joint along the Weld Line (X-Axis) and the Line Vertical to the Weld Line Passing through the Center of the Weld (Y-Axis)

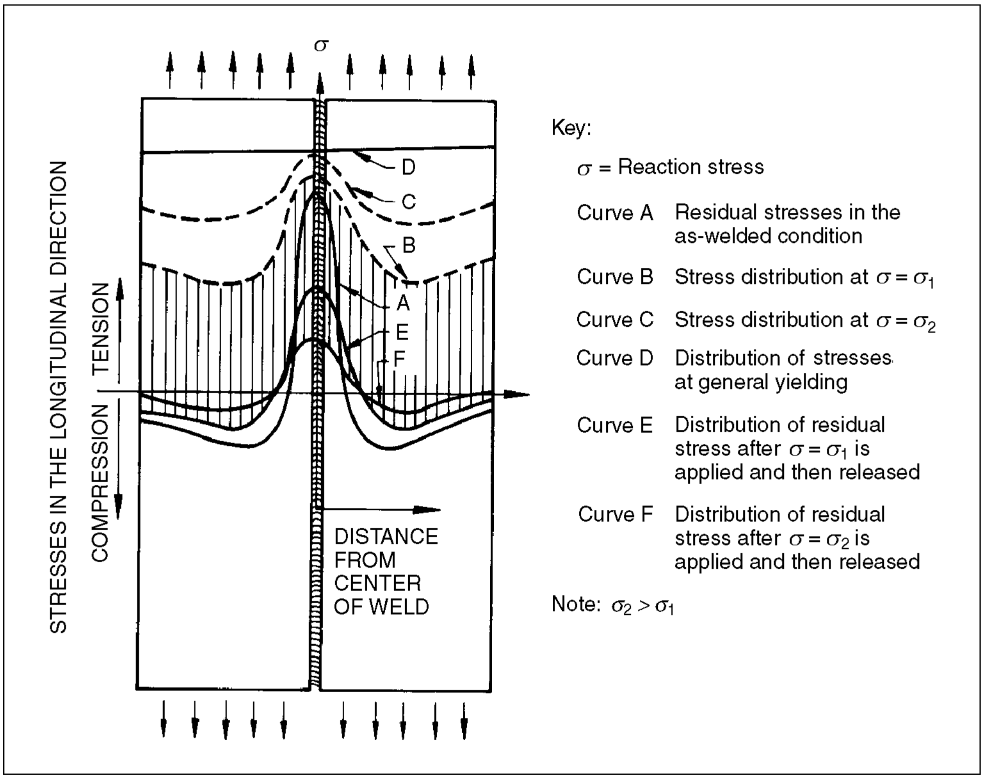
while compressive stress is generated at both ends of the joint.

If the lateral contraction of the joint is restrained by an external constraint, tensile stress approximately uniform along the length of the weld is added to the residual stress as reaction stress. This is illustrated by Curve 2 in Figure 7.11(C). An external constraint affects the magnitude of the residual stress but has little influence on its distribution.

Residual stress in the thickness direction, σ_z, can become significant in weldments over 1 in. (25 mm) thick.

EFFECTS OF RESIDUAL STRESS

Residual stress decreases the fracture strength of welded structures only when certain conditions exist. However, the loss of strength can be drastic under these conditions. In general, the effects of residual stress are significant if fractures can take place under low applied stress.



Source: Data from Wilson, W. M., and C. C. Hao, 1947, Residual Stresses in Welded Structures, *Welding Journal* 26(5): 295-s–320-s.

Figure 7.12—Effect of Uniform External Loads on Residual Stress Distribution in a Welded Butt Joint

CHANGE IN WELDMENTS SUBJECTED TO TENSILE LOADING

Figure 7.12 illustrates changes in residual stress when a welded butt joint is subjected to tensile loading.[10] Curve A depicts the lateral distribution of the longitudinal residual stress in the as-welded condition. When uniform tensile stress σ_1 is applied, the stress distribution is as shown by Curve B. The stress in the areas near the weld reaches yield stress, and most of the increase in stress occurs in areas farther away from the weld. When the applied tensile stress increases to σ_2, the stress distribution is as shown by Curve C. As the level of applied stress increases, the stress distribution across the weld becomes more uniform (i.e., the effect of the residual stress on the distribution of the stress decreases).

When the level of applied stress is further increased, general yielding takes place (i.e., yielding occurs across the entire cross section). The distribution of stress at general yielding is shown by Curve D. Beyond general yielding, the effect of residual stresses on the stress distribution virtually disappears.

The next consideration is the distribution of residual stress after the tensile loads are released. Curve E depicts the residual stress that remains after unloading when tensile stress σ_1 is applied to the weld and then released. Curve F shows the residual stress distribution when the tensile stress σ_2 is applied and then released.

Compared to the original pattern of distribution, shown in Curve A, the residual stress distribution after loading and unloading is less severe, as shown in Curves E and F. As the level of loading increases, the residual stress distribution after unloading becomes more nearly uniform (i.e., the effect of welding residual stress on the overall distribution of stress across the welded joint decreases).

10. Wilson, W. M., and C. C. Hao, 1947, Residual Stresses in Welded Structures, *Welding Journal* 26(5): 295-s–320-s.

Based on this analysis, the effects of residual welding stress can be summarized as follows:

1. The effect of residual welding stress on the performance of welded structures is significant only on phenomena that occur under low applied stress, such as brittle fracture, fatigue, and stress corrosion cracking;
2. As the level of applied stress increases, the effect of residual stresses decreases;
3. The effect of residual stress is negligible on the performance of welded structures under an applied stress greater than the yield strength; and
4. The effect of residual stress tends to decrease after repeated loading.

BRITTLE FRACTURE OR UNSTABLE FRACTURE UNDER LOW APPLIED STRESS

Extensive studies have been conducted on the effects of residual stress on brittle fractures in welded steel structures. Data obtained from brittle fractures in ships and other structures differ from experimental results obtained with notched specimens. Actual fractures have occurred at stress levels far below the yield strength of the material. However, the nominal fracture stress of a notched specimen is as high as the yield strength, even when the specimen contains very sharp cracks. Under certain test conditions, the complete fracture of a specimen has occurred although the magnitude of the applied stress was considerably below the yield stress of the material.[11]

Figure 7.13 illustrates the general fracture-strength tendencies of welded carbon-steel specimens at various temperatures as well as the effects of a transverse sharp notch and residual stress on fracture strength.[12] When a specimen contains no sharp notch, fracture occurs at the ultimate strength of the material, as represented by Curve PQR. When a specimen contains a sharp notch (but no residual stress), fracture occurs at the stress represented by Curve PQST. When the test temperature is higher than the fracture transition temperature, T_f, a high-energy (shear-type) fracture occurs at high stress. When the test temperature is below T_f, the appearance of the fracture changes to a low-energy (cleavage) type, and the stress at fracture decreases to near the yield strength.

When a notch is located in areas where high residual tensile stress is present, the following types of fractures can occur:

1. At temperatures higher than the fracture transition temperature, T_f, fracture stress is the ultimate strength (Curve PQR), and residual stress has no effect on fracture stress;
2. At temperatures lower than T_f but higher than the crack-arresting temperature, T_a, a crack may initiate at a low stress, but it will not propagate;
3. At temperatures lower than T_a, one of the following two phenomena can occur, depending upon the stress level at fracture initiation:

   (a) If the stress is below the critical stress, *VW*, the crack reaches a standstill after propagating a short distance, or
   (b) If the stress is higher than critical stress, *VW*, complete fracture will occur.

The effect of residual stress on unstable fractures has been analyzed using the concepts of fracture mechanics.[13] This analysis indicates that an unstable fracture can develop from small cracks that would normally be stable if residual stress were not present. When a small subcritical flaw lies in a region that is either free of or contains compressive residual stress, this stress does not contribute to the intensity of the stress at the tip of the discontinuity. If the tip of the flaw occurs in a region having tensile residual stress, this tensile residual stress would add to the applied stress and increase the intensity of the stress around the tip of the discontinuity. This increase in intensity may cause the flaw to crack and extend until the tip is outside the region containing residual stress. At this point, the crack may cease or continue to grow, depending on its length and the intensity of the stress. Thus, residual stress is localized, and fracture performance is affected only within the region of the residual stress field.

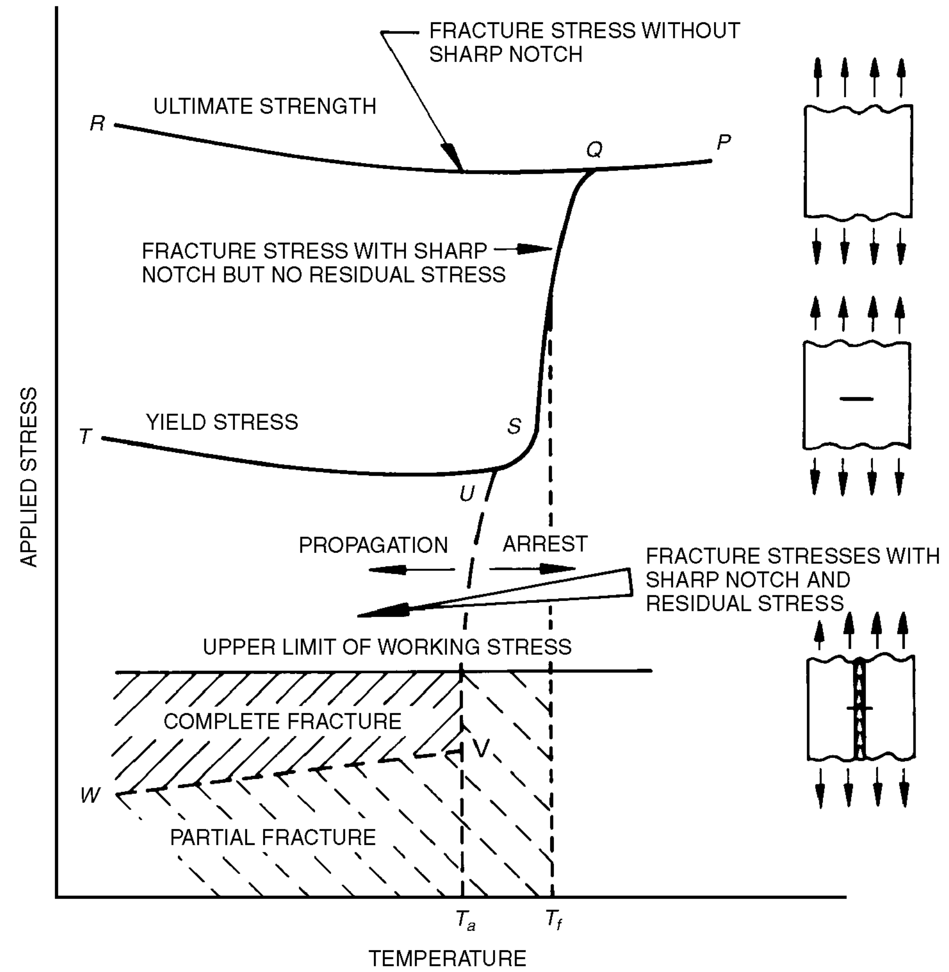
BUCKLING UNDER COMPRESSIVE LOADING

Failures due to instability or buckling sometimes occur in metal structures such as slender bars, beams, and thin plates when these are subjected to compressive axial loading, bending, or torsional loading. Residual compressive stress decreases a metal structure's buckling strength. Initial distortions caused by residual stress also decrease the buckling strength.

Columns under Compressive Loading

Residual stress can significantly reduce the buckling strength of columns fabricated by welding, particularly

11. Hall, W. S., H. Kihara, W. Soete, and A. A. Wells, 1967, *Brittle Fracture of Welded Plate*, Englewood Cliffs, New Jersey: Prentice Hall.
12. Kihara, H., and K. Masubuchi, 1959, Effect of Residual Stress on Brittle Fracture, *Welding Journal* 38(4): 159-s–168-s.
13. These concepts are described in more detail in Chapter 6 in this volume.



Key:
T_a = Crack-arresting temperature
T_f = Fracture transition temperature

Source: Adapted from Kihara, H., and K. Masubuchi, 1959, Effect of Residual Stress on Brittle Fracture, *Welding Journal* 38(4): 159–168-s, Figure 5.

Figure 7.13—Effects of Sharp Notch and Residual Stress on Fracture Strength

when these are made from universal mill plate.[14,15] However, the effects experienced by columns fabricated from universal mill plate are similar to those experienced by comparable hot-rolled columns. Columns made from universal mill plate and hot-rolled columns also have very high residual tensile stress at the intersections of the flanges and webs as well as residual compressive stress at the outer ends of the flanges.

Columns made from oxygen-cut plates normally contain residual tensile stress in the outer areas of the flange. As can be observed in Figure 7.14, columns fabricated from flame-cut plates and stress-relieved columns exhibit better resistance to buckling than columns fabricated from universal mill plate. In this case, the residual stress that results from preparing the plate by oxygen cutting and the stress that results from subsequent welding into the column section combine to counterbalance each other with respect to buckling strength. The performance of these columns should be about equivalent to that of hot-rolled plates. Thus, most welded fabricated columns utilize flame-cut rather than universal mill plate.

Plate and Plate Structures under Compressive Loading

Residual stress in the direction parallel to the weld line is compressive in the regions farther away from the weld, while it is tensile in regions near the weld [see Figure 7.11(B)]. Consequently, the effects of residual stress on the buckling strength of welded structures are complex. Residual stress may reduce buckling strength under some conditions and increase it under others.

Both residual stress and distortion exist in many structures. They exert complex effects on the buckling strength of welded structures.[16] As a rule, out-of-plane distortion causes considerable reduction in the buckling strength.

LIVE GRAPH
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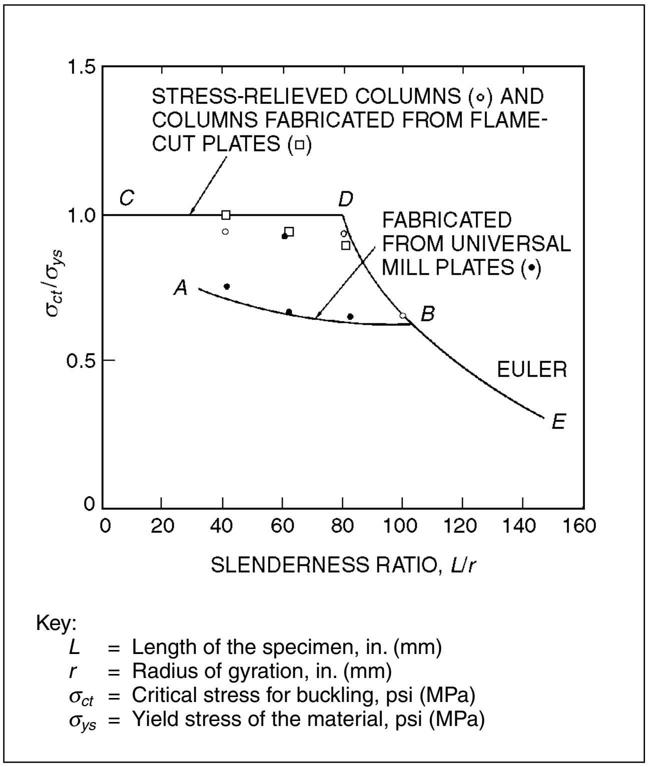


Source: Adapted from Kihara, H., and Y. Fujita, 1960, The Influence of Residual Stresses on the Instability Problem, in *Influence of Residual Stresses on Stability of Welded Structures and Structural Members*, London: International Institute of Welding.

Figure 7.14—Effects of Residual Stress on the Buckling Strength of Columns

FATIGUE STRENGTH

Fatigue strength, the number of cycles required to fracture a specimen under a given load or the endurance limit, increases when a specimen contains compressive residual stress, especially on its surface. For example, experimental studies have shown that the local spot heating of certain types of welded specimens increases the fatigue strength.[17] On the other hand, it is possible that residual stress is relieved during cyclic loading and that its effects on the fatigue strength of weldments are negligible.

Surface smoothness is an important characteristic of fatigue fracture because most fatigue cracks originate at the surface.[18] The removal of weld reinforcement and smoothing of surface irregularities, including undercut,

14. Plate-rolling mills are generally considered in two very broad design classifications. One type includes the universal mills, which are characterized by vertical rolls preceding and following the horizontal rolls. The vertical and horizontal rolls are integrated into a single mill unit and work the stock simultaneously. The second type includes the sheared plate mills, some of which may include edge-working equipment. Further details are given in United States Steel, 1980, *The Making, Shaping, and Treating of Steel,* 10th ed., Pittsburgh: Association of Iron and Steel Engineers.
15. Kihara, H., and Y. Fujita, 1960, The Influence of Residual Stresses on the Instability Problem, in *Influence of Residual Stresses on Stability of Welded Structures and Structural Members*, London: International Institute of Welding; Tall, L., A. W. Huber, and L. S. Beedle, 1960, Residual Stress and the Instability of Axially Loaded Columns, in *Influence of Residual Stresses on Stability of Welded Structures and Structural Members,* London: International Institute of Welding.
16. See Reference 3.

17. Gurney, T. R., 1979, *Fatigue of Welded Structures,* 2nd. ed., Cambridge: Cambridge University Press.
18. See Reference 3.

Table 7.1
Environments Producing Stress Corrosion Cracking

Alloy	Sensitive Environment
Low-alloy steels	Nitrates, hydroxides, hydrogen sulfide
Chromium stainless steels (greater than 12% Cr)	Halides, hydrogen sulfides, steam
Austenitic stainless steels (18% Cr–8% Ni)	Chlorides, hydroxides
Aluminum alloys	Sodium chloride, tropical environments
Titanium alloys	Red fuming nitric acid, chlorinated hydrocarbons

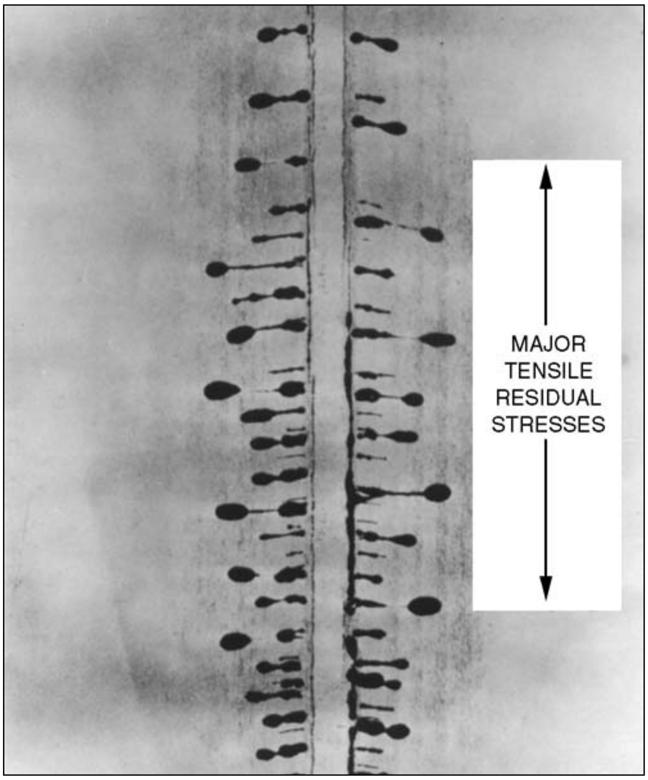
are effective in reducing stress concentrations and increasing the fatigue strength of weldments.[19]

CRACKING UNDER HOSTILE ENVIRONMENTAL CONDITIONS

In the presence of a hostile environment, residual stress can cause cracking in metals without any applied loads. Both ferrous and nonferrous alloys can be susceptible to stress-corrosion cracking. Examples of sensitive combinations of metals and environments are presented in Table 7.1.

Studies of the susceptibility of high-strength steels to hydrogen-induced cracking have been utilized to indicate the distribution of residual stress in welds.[20] The crack pattern along a welded butt joint fabricated from oil-quenched and tempered SAE 4340 steel plates is shown in Figure 7.15. The crack pattern was revealed by the use of a liquid penetrant test. After the test, some penetrant came out from cracks, causing the blotting of penetrant near the crack tips. Therefore, round blots at the crack ends are not voids, but simply blotted penetrant. Longitudinal and transverse cracking is apparent.

The longitudinal cracks appear in the heat-affected zone, while the transverse cracks occur in the heat-affected zone and the base metal. The residual tensile stress is transverse to the weld in the heat-affected zone, as indicated by the longitudinal cracks. The residual tensile stress is longitudinal farther away from the weld, as indicated by the transverse cracks. The transverse cracks are longer and more numerous near the mid-length of the weld than near the ends. This indicates that the residual stress is lower toward the ends of the weld.



Note: The crack pattern was revealed by the use of the liquid penetrant test. After the test, some amounts of penetrant came out of the cracks, causing the blotting of penetrant near the tips of the cracks. Therefore, the round blots at the ends of the cracks are not voids, but simply blots of penetrant.

Source: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 4.16.

Figure 7.15—Crack Pattern in a Simple Butt Joint

MEASUREMENT OF RESIDUAL STRESS IN WELDMENTS

The residual stress gradients in weldments are often as high as 500 ksi/in. (140 MPa/mm), requiring measurements with a high spatial and volume resolution. Because of these high gradients, many measurements must be taken in a small area to map the stress distribution in the weldment.

19. Fatigue life is also discussed in Chapters 5, 10, and 11 in this volume.
20. Masubuchi, K., and D. C. Martin, 1966, Investigation of Residual Stresses by Use of Hydrogen Cracking. Part II, *Welding Journal* 45(9): 401-s–418-s; Masubuchi, K., and D. C. Martin, 1961, Investigation of Residual Stresses by Use of Hydrogen Cracking. Part I, *Welding Journal* 40(12): 553-s–563s.

Table 7.2
Classification of Techniques for the Measurement of Residual Stress

A-1	Stress relaxation using electric and mechanical strain gauges	
	Techniques applicable primarily to plates	
		1. Sectioning using electric resistance strain gauges
		2. Gunnert drilling
		3. Mathar-Soete drilling
		4. Stäblein successive milling
	Techniques applicable primarily to solid cylinders and tubes	
		5. Heyn-Bauer successive machining
		6. Mesnager-Sachs boring out
	Techniques applicable primarily to three-dimensional solids	
		7. Gunnert drilling
		8. Rosenthal-Norton sectioning
A-2	Stress relaxation using apparatus other than electric and mechanical strain gauges	
		9. Grid system dividing
		10. Brittle coating drilling
		11. Photoelastic coating drilling
B	Diffraction	
		12. X-ray film
		13. Conventional scanning X-ray diffractometer
		14. Stress X-ray diffractometer
		15. Neutron diffraction
C	Cracking	
		16. Hydrogen-induced cracking
		17. Stress corrosion cracking

A number of techniques are used to measure residual stress in metals. Table 7.2 classifies the available measurement techniques into the following groups: (1) stress relaxation, (2) diffraction, and (3) cracking.[21]

MEASUREMENT BY STRESS RELAXATION

In Group A-1 in Table 7.2, residual stress is determined by measuring the elastic strain release. These techniques are based on the known fact that the strains that occur during unloading are elastic even when the material has undergone plastic deformation. Therefore, it is possible to determine residual stress without knowing the history of the material. The determination of residual stress takes places when the stress is relaxed by cutting the specimen into pieces or by removing a piece from the specimen. In most cases, electric or mechanical strain gauges are used to measure the strain release.

21. See Reference 3.

Strain release during stress relaxation (Group A-2) can be determined using a grid system, brittle coatings, or photoelastic coatings. An inherent disadvantage of these stress-relaxation techniques is that they are destructive, as the specimen must be partly or entirely sectioned. These techniques are also time consuming. Nevertheless, stress-relaxation techniques are widely used to measure residual stress in weldments.

A variety of stress-relaxation techniques are utilized to determine residual stress, depending upon the method used to section the specimen. Some techniques are applicable primarily to plates, while others are applicable to cylinders, tubes, or three-dimensional solids. Four techniques for the measurement of residual stress can be used for weldments. Two techniques apply primarily to thin plates, whereas the other two apply primarily to solids. All four employ electric or mechanical strain gauges. The range of and the advantages and disadvantages of these four techniques are discussed below and summarized in Table 7.3.

Table 7.3
Stress-Relaxation Techniques for the Measurement of Residual Stress

Technique	Applications	Advantages	Disadvantages
1. Sectioning using electric-resistance strain gauges	Relative all-around use, with the measuring surface placed in any position; used for plate, cylinders, and tubes.	Reliable method; simple principle; high accuracy.	Destructive; gives average of stress over the area of the material removed from the plate; not suitable for measuring locally concentrated stress; machining is sometimes expensive and time consuming.
2. Mathar-Soete drilling	Laboratory and field work on horizontal, vertical, and overhead surfaces; used for plate.	Simple principle; causes little damage to the test piece; convenient to use on welds and base metal.	Drilling causes plastic strains at the periphery of the hole, which may displace the measured results. The method must be used with great care.
3. Gunnert drilling	Laboratory and field work. The surface must be substantially horizontal; may be used for plate, cylinders, or tubes, but actual usage is limited due to limited accuracy.	Robust and simple apparatus; semidestructive; damage to the test object can be easily repaired.	Relatively large margin of error for stress measured in a perpendicular direction The underside of the weldment must be accessible for the attachment of a fixture. The method entails manual training.
4. Rosenthal-Norton sectioning	Laboratory measurements; use limited to thick plate.	Fairly accurate data can be obtained when measurements are carried out carefully.	Troublesome, time-consuming, and completely destructive.

Sectioning Technique Using Electric-Resistance Strain Gauges

With this technique, electric-resistance strain gauges are mounted on the surface of the test structure or specimen.[22] A small piece of metal containing the gauges is then removed from the structure, as shown in Figure 7.16. The strain that takes place during the removal of the piece is determined. The piece removed is small enough so that the remaining residual stress may be neglected. Therefore, the strain measured is elastic strain that has resulted from the residual stress distribution in the specimen.

Stated mathematically,

$$\begin{aligned} \bar{\varepsilon}_x &= -\varepsilon'_x \\ \bar{\varepsilon}_y &= -\varepsilon'_y \\ \bar{\gamma}_{xy} &= -\gamma'_{xy} \end{aligned} \tag{7.9}$$

where

ε'_x, ε'_y, and γ'_{xy} = Elastic strain components of the residual stress, and
$\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$, and $\bar{\gamma}_{xy}$ = Measured values of the strain components.

The negative sign used in Equation (7.9) indicates that the strains are in opposite directions.

The residual stress can then be determined by substituting the expressions shown in Equation (7.9) into those presented in Equation (7.3) and solving the simultaneous equations for σ_x, σ_y, and σ_{xy}. Thus,

$$\begin{aligned} \sigma_x &= \frac{-E}{1-\upsilon^2}\left[\bar{\varepsilon}_x + \upsilon\bar{\varepsilon}_y\right] \\ \sigma_y &= \frac{-E}{1-\upsilon^2}\left[\bar{\varepsilon}_y + \upsilon\bar{\varepsilon}_x\right] \\ \tau_{xy} &= -G\bar{\gamma}_{xy} \end{aligned} \tag{7.10}$$

where

σ_x = Normal residual stress in the x-direction, psi (MPa);
E = Modulus of elasticity (Young's modulus) of the material, psi (MPa);
υ = Poisson's ratio;

22. In the resistance-type bonded-strain-gauge technique, gauges made from either metallic wire or foil materials are bonded on the specimen. As the specimen is strained, the resistance of the gauges changes, and the magnitude of strain is determined by measuring the resistance change. Information on electric strain gauges is available from various sources, including Hetény, M., 1950, *Handbook of Experimental Stress Analysis*, New York: John Wiley and Sons.

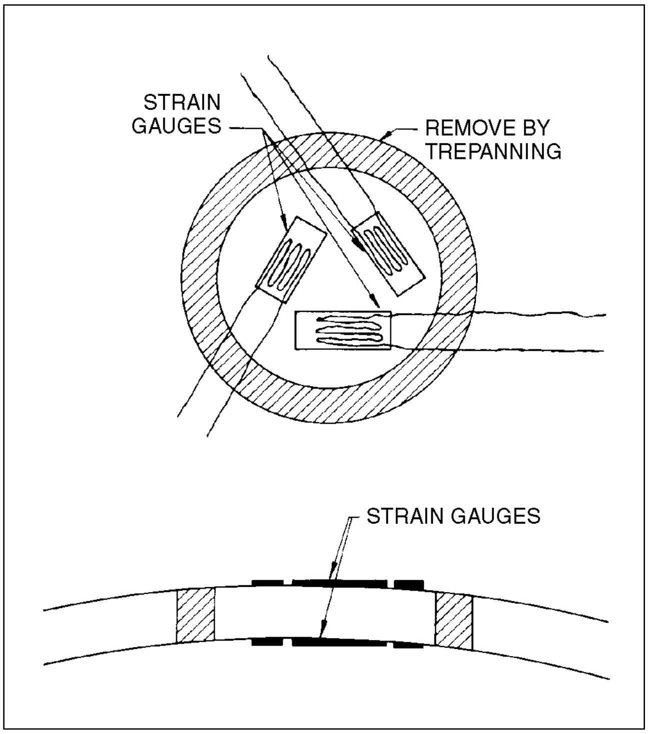


Figure 7.16—Complete Stress-Relaxation Technique Applied to a Plate

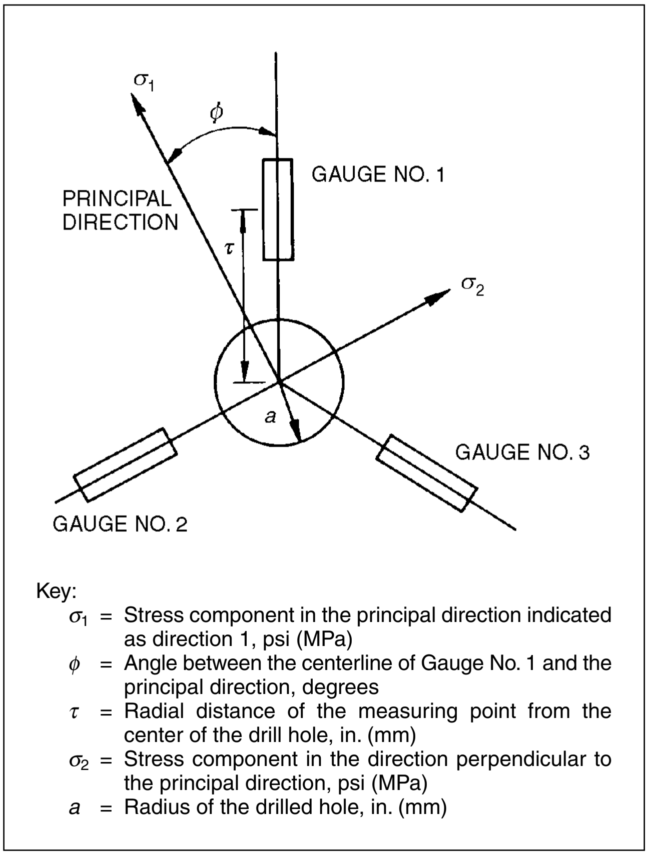


Figure 7.17—Star Arrangement (120°) of Strain Gauges for the Mather-Soete Drilling Technique

$\bar{\varepsilon}_x$ = Measured value of strain component;
$\bar{\varepsilon}_y$ = Measured value of strain component;
σ_y = Normal residual stress in the y-direction, psi (MPa); and
G = $E/(1 - \nu^2)$ Rigidity of the material, psi (MPa).

It is advisable to make strain measurements on the surfaces of both sides of the plate because residual stress may be caused by bending. The mean value of the strains measured on both surfaces represents the normal stress component, while the difference between the strains on both surfaces represents the bending stress component.

Mathar-Soete Drilling Technique

The hole method of measuring stress was first proposed and used by Mathar[23] and was further developed by Soete.[24] When a small circular hole is drilled in a plate containing residual stress, the stress in the areas around the hole is partially relaxed. The residual stress that existed in the drilled area is determined by measuring the stress relaxation in the areas around the drilled hole.

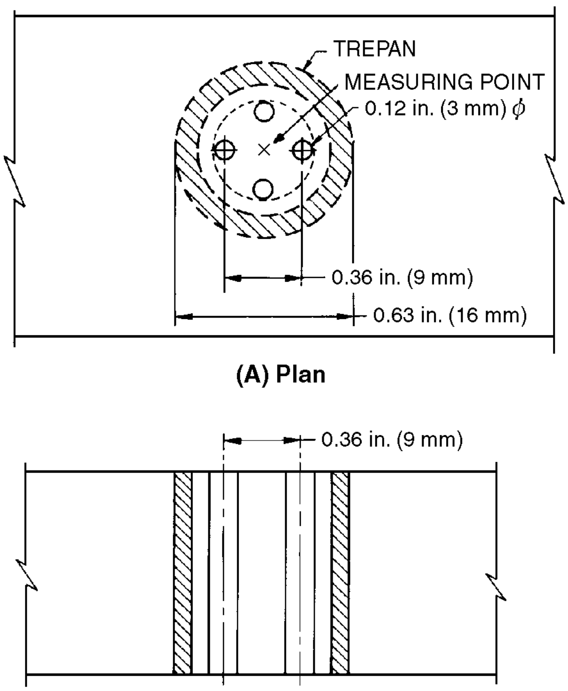
This technique is shown in Figure 7.17. Three strain gauges are placed at 120° from each other, and then a hole is drilled in the center. The magnitudes and directions of the principle stresses are calculated by measuring strain changes at the three gauges.

Gunnert Drilling Technique

The Gunnert technique,[25] illustrated in Figure 7.18, involves the drilling of four 0.12 in. (3 mm) holes through the plate perpendicular to the surface at the measuring point in a circle 0.35 in. (9 mm) in diameter.

23. Mathar, J., 1934, Determination of Metal Stress by Measuring the Deformation around Drill Holes, *Transactions of the American Society of Mechanical Engineers* 86(n.n.): 249–254.
24. Soethe, W., 1949, Measurement and Relaxation of Residual Stresses, *Welding Journal* 28(8): 354-s–364-s.

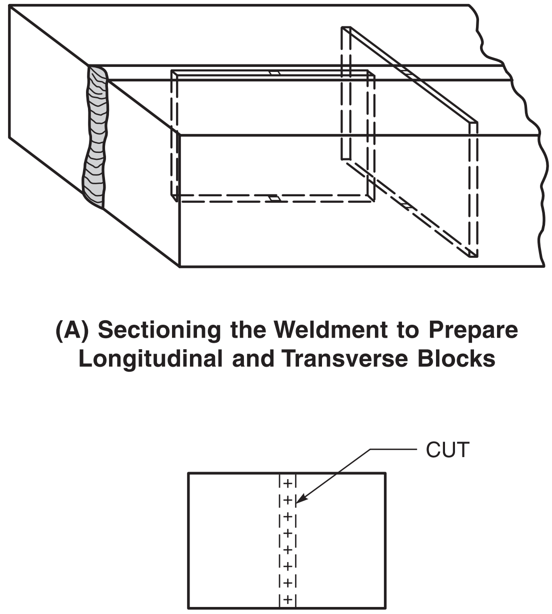
25. Gunnert, R., 1958, Method for Measuring Tri-Axial Residual Stresses, *Welding Research Abroad* 4(10): 17–25.



(A) Plan

(B) Side View

Figure 7.18—Gunnert Drilling Technique: (A) Plan and (B) Side View



(A) Sectioning the Weldment to Prepare Longitudinal and Transverse Blocks

(B) Further Sectioning of Block

Source: Adapted from Rosenthal, D., and J. T. Norton, 1945, A Method for Measuring Triaxial Residual Stress in Plates, *Welding Journal* 24(5): 295-s–307-s, Figure 1.

Figure 7.19—Rosenthal-Norton Sectioning Method for Measuring Residual Stresses in a Thick Weld

The diametrical distance between these holes at different levels below the surface of the plate is measured by means of a specially designed mechanical gauge. The perpendicular distance between the plate surface and the gauge location at different levels below the surface is also measured.

A groove 0.63 in. (16 mm) from the measuring point is then trepanned around the holes in steps, and the same measurements are made. The residual stress present in the interior of the specimen can be calculated based on the measurement data.

Rosenthal-Norton Sectioning Technique

Rosenthal and Norton proposed a technique for determining the residual stress in a thick weldment.[26] Two narrow blocks with the full thickness of the plate, one parallel to the weld and the other transverse to the weld, are cut from the weld, as shown in Figure 7.19.

26. Rosenthal, D., and J. T. Norton, 1945, A Method for Measuring Triaxial Residual Stress in Plates, *Welding Journal* 24(5): 295-s–307-s.

The blocks should be made thin enough so that it may then be assumed that the operation has relieved practically all of the residual stress acting in the direction parallel to their long axis. At the same time, the blocks should be long enough with respect to the thickness of the plate (twice the thickness or more, if possible). The stress that has been relieved in the central portion of the block is very nearly a linear function of the thickness. In other words, if the value of the stress is known on the top and bottom faces of the plate, the values of the stress relieved throughout the thickness can be computed.

The next step involves the determination of the residual stresses still remaining in the blocks. This can be done by mounting strain gauges on the walls of the blocks and then measuring the strain relaxation that results from slicing the blocks into small pieces. Two blocks, one longitudinal and one transverse, must be cut in order to determine the three-dimensional stress distribution. Since two blocks cannot be cut from the same spot, the layout must be arranged so as to make use of the symmetry of the specimen or interpolation.

The experimental determination of the three-dimensional distribution of residual stress in a heavy weldment involves complex, time-consuming operations. In order to obtain accurate distributions, a careful plan for sectioning the weld and processing measured data must be developed.

MEASUREMENT BY DIFFRACTION

Elastic strains in metals can be determined by measuring the strain on lattice planes using diffraction techniques (Group B in Table 7.2). When a polycrystalline metal is placed under stress, the elastic strains in the metal are manifested in the crystal lattice of the individual grains of the metal. The stress applied externally or residual within the metal, when below its yield point, is taken up by interatomic strain. The diffraction techniques are capable of actually measuring the interatomic spacings, which are indicative of strain. Stress values are obtained from these elastic strains by identifying the elastic constraints of the material and assuming that stress is proportional to strain. This is a reasonable assumption for homogeneous, nearly isotropic materials as are most metals of practical concern. Elastic strains in the metal can be determined nondestructively without machining or drilling.[27] Several X-ray and neutron-diffraction techniques are currently available.

Early measurement techniques employed film technologies, but the measurements were so slow and tedious that few practical results were obtained.[28] By 1975, conventional scanning X-ray diffractometers were used almost exclusively for X-ray residual stress measurements. More recently, instruments based upon position-sensitive X-ray detectors and designed specifically to perform X-ray residual stress measurements have been developed.[29] These stress X-ray diffractometers provide very rapid (in a few seconds or less), nondestructive residual stress measurements that can be taken in the field (e.g., on bridge weldments or gas pipelines). Used for moving and static parts, these diffractometers can be employed to measure residual stress on pin bearings less than 0.04 in. (1 mm) in diameter. Moreover, X-ray diffraction techniques measure surface stresses 0.0001 in. to 0.002 in. (2 μm to 50 μm) into the surface, thereby providing a means for the resolution of high stress gradients with depth into the surface. Unfortunately, however, subsurface and internal stress cannot be measured nondestructively.

In order to measure internal stress with X-ray techniques, the weldment must be systematically sectioned, and the surfaces to be measured must be electropolished.[30] Nonetheless, these new stress X-ray diffractometers have overcome the precision, accuracy, and speed inadequacies inherent to film and conventional scanning X-ray diffractometers. These X-ray techniques, applied with stress diffractometers, are highly accurate and provide the best stress resolution when high stress gradients exist.[31]

Neutron diffraction techniques are capable of measuring internal stress without destroying the weldment. Unlike the relatively low-energy X-rays used in diffraction, which are absorbed in a few hundred microinches (10 to 20 micrometers), neutrons penetrate several inches of metal and can be diffracted from the internal volumes of a metal weldment to measure internal residual stresses. The volume resolution of the neutron stress measurements is 6×10^{-4} in.^{3} (10 mm^3). Neutron diffraction stress measurements can be performed only at certain nuclear reactor facilities, however.

MEASUREMENT BY CRACKING

Techniques are also available for the study of residual stress by means of observing the cracks in the specimen (Group C in Table 7.2) (see Figure 7.15). Cracks may be induced by hydrogen or stress corrosion. Cracking techniques are useful for studying residual stress in complex structural models that have complicated residual stress distributions. However, these techniques provide qualitative rather than quantitative data.

RESIDUAL STRESS DISTRIBUTION PATTERNS IN TYPICAL WELDS

This section describes the residual stress distributions that are typically found in several common weld joint types and welded structures. These include welded butt joints, plug welds, welded beams and column shapes, and welded pipes.

27. Ruud, C. O., 2000, Residual Stress Measurement, in *ASM Handbook*, Vol. 8, H. Kuhn and D. Medlin, eds., Materials Park, Ohio: ASM International, pp. 898–899.
28. Boldstad, D. A., and W. E. Quist, 1965, The Use of a Portable X-Ray Unit for Measuring Residual Stresses in Aluminum, Titanium, and Steel Alloys, in *Advances in X-Ray Analysis,* D. A. Boldstad and W. E. Quist, eds., New York: Plenum Press.
29. Ruud, C. O., 1983, Position-Sensitive Detector Improves X-Ray Powder Diffraction, *Industrial Research and Development,* n/v (January): 84–86.
30. Ruud, C. O., J. A. Josef, and D. J. Snoha, 1993, Residual Stress Characterization of Thick-Plate Weldments Using X-Ray Diffraction, *Welding Journal* 72(3): 87-s–91-s.
31. See Reference 29.

WELDED BUTT JOINT

The typical distribution of longitudinal and transverse residual stress in a butt joint welded in a single pass has been discussed previously and is shown in Figure 7.11.

PLUG WELD

Figure 7.20 depicts the typical distribution of residual stress in a circular plug weld. In the weld and surrounding areas, tensile stress as high as the yield strengths of the materials was produced in both the radial and tangential directions.[32] In areas away from the weld, the radial stress, σ_r, was tensile, whereas the tangential stress, σ_Φ, was compressive. Both types of stress decreased with increasing distance, r, from the weld.

WELDED BEAM AND COLUMN SHAPES

Typical distributions of residual stress in welded shapes are shown in Figure 7.21. Figure 7.21(A) demonstrates the residual stress and distortion produced in a welded T-section. In a section some distance from the end of the column, Section X–X, high tensile residual stress in the direction parallel to the axis is produced in areas near the weld. In the flange, the stress is tensile in areas near the weld and compressive in areas father away from the weld. Tensile stress in areas near the upper edge of the web is a result of the longitudinal bending distortion of the shape caused by the longitudinal shrinkage of the weld. Angular distortion may also take place.

Figures 7.21(B) and (C) show typical distributions of residual stress in a welded H-section and a welded box section, respectively. The residual stress shown runs parallel to the axis. Tensile stress occurs in areas near the welds, while compressive stress is present in areas farther away from the welds.

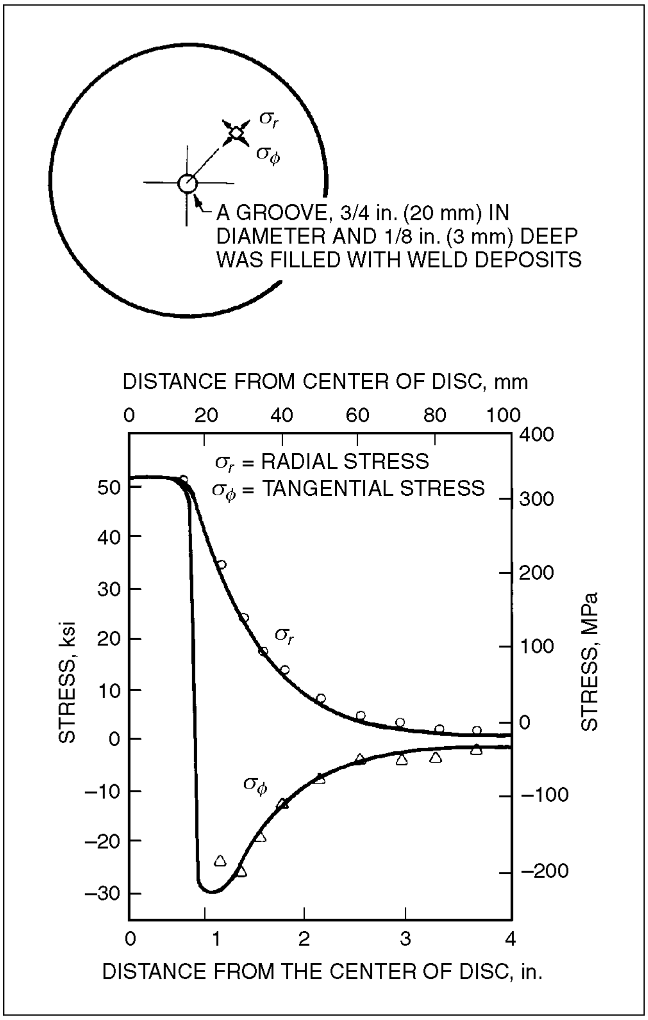


Figure 7.20—Effect of Distance from the Center of a Plug Weld on Radial and Tangential Residual Stress

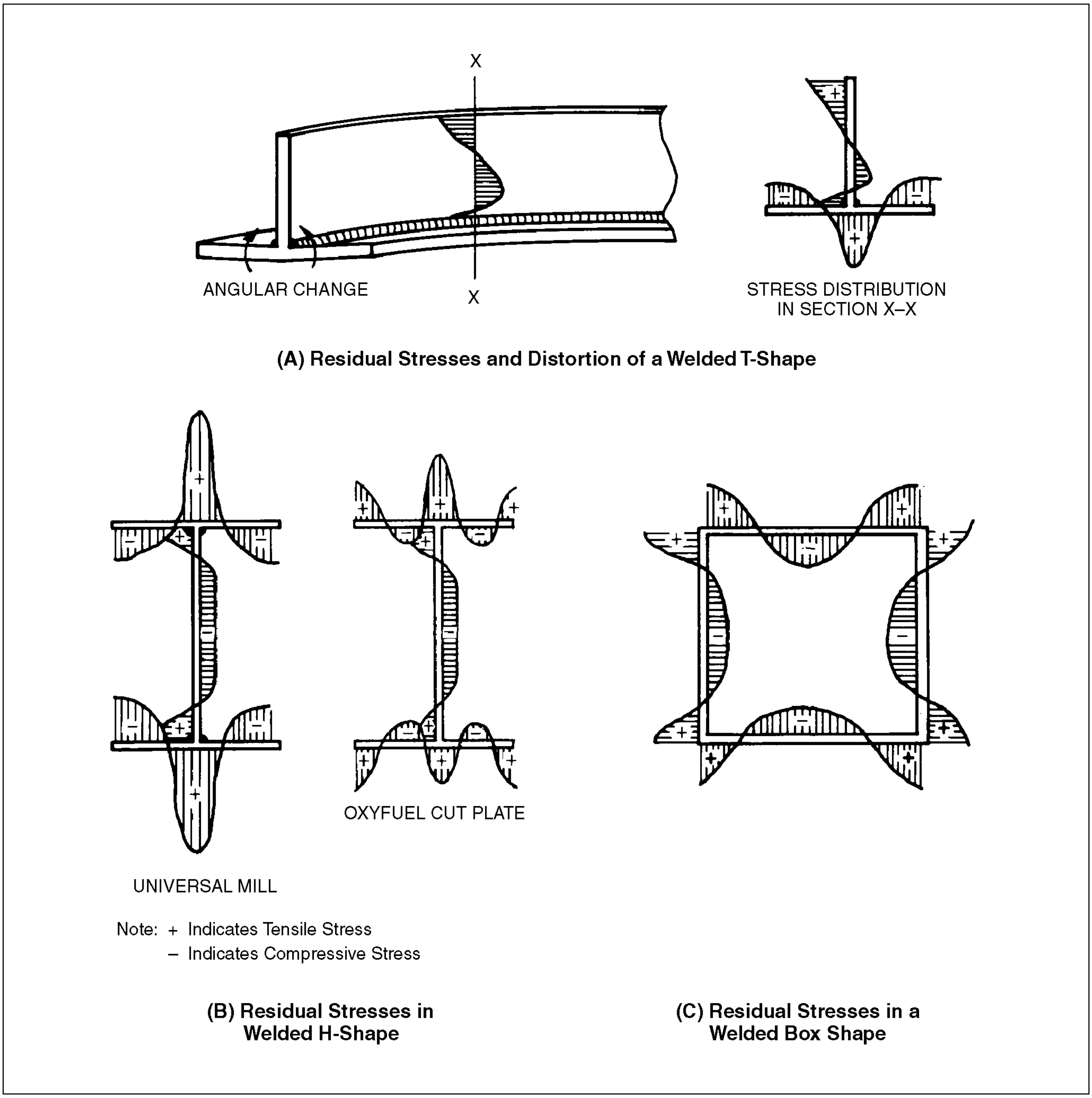
WELDED PIPES

The distribution of residual stress in welded pipes is complex. In girth-welded pipes, for example, shrinkage of the weld in the circumferential direction induces both shearing force, Q, and bending moment, M, as shown in Figure 7.22. The angular distortion caused by welding also induces a bending moment. The distribution of residual stress in pipes is affected by the following:[33]

1. Diameter and wall thickness of the pipe;
2. Design of the weld joint (square, butt, V, for example); and
3. Welding procedure and sequence (welded on the outside only; welded on both sides, outside first; or welded on both sides, inside first).

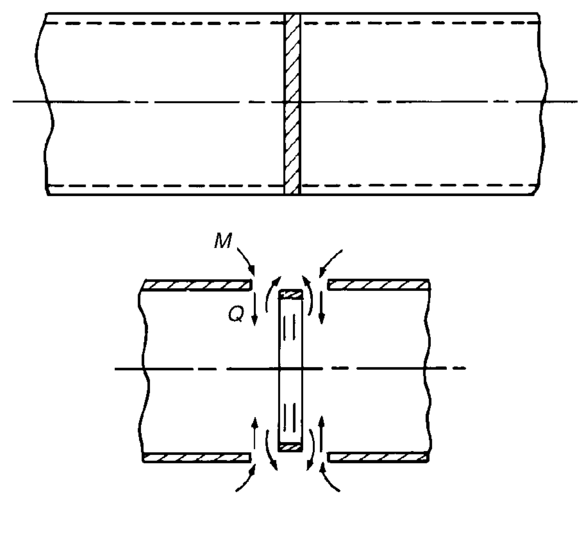
32. Kihara, H., M. Watanabe, K. Masubuchi, and K. Satoh, 1959, Researches on Welding Stress and Shrinkage Distortion in Japan, Vol. 4 of *60th Anniversary Series of the Society of Naval Architects of Japan*, Tokyo: Society of Naval Architects of Japan.

33. See Reference 3.



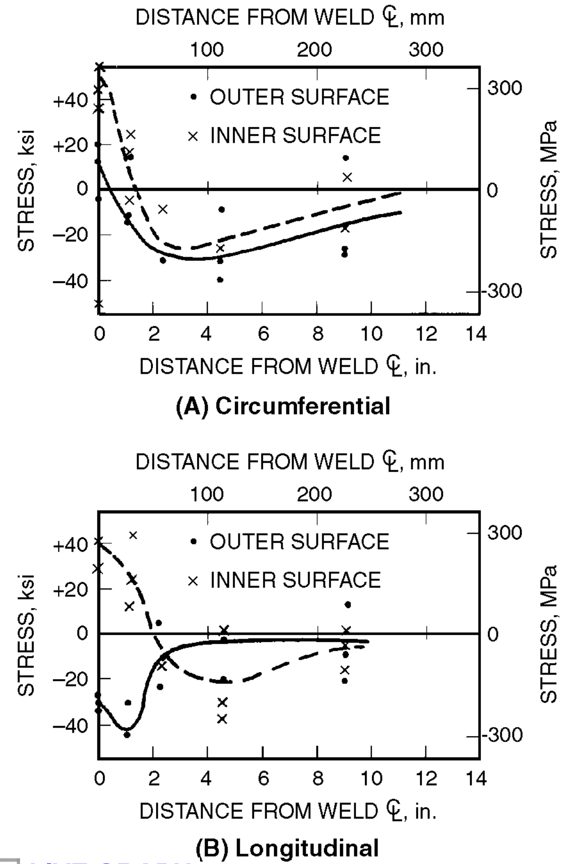
Sources: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press; Figure 6.17; data from Rao, N. R. N., F. R. Estuar, and L. Tall, 1964, Residual Stresses in Welded Shapes, *Welding Journal* 43(7): 295-s–306-s.

Figure 7.21—Typical Types of Residual Stress in Welded Shapes: (A) Residual Stress and Distortion of a Welded T-Shape; (B) Residual Stress in Welded H-Shapes; and (C) Residual Stress in a Welded Box Shape



Source: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.20.

Figure 7.22—Bending Moment, *M*, and Shrinkage Force, *Q*, and Caused by Residual Stress in a Girth-Welded Pipe



Source: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.21; data from Burdekin, F. M., 1963, Local Stress Relief of Circumferential Butt Welds in Cylinders, *British Welding Journal* 10(9): 483–490.

Figure 7.23—Residual Stress in a Girth Weld in a Low-Carbon Steel Pipe: (A) Circumferential and (B) Longitudinal

A number of investigators, including Watanabe, Minehisa, and Onoue,[34] Burdekin,[35] and Rybicki, McGuire, Merrick, and Wert[36] have investigated residual stress in welded pipe in various dimensions produced with a variety of welding procedures and conditions. As an example, Figure 7.23 illustrates the residual stress resulting from a circumferential weld in a low-carbon steel pipe. The pipe is 30 in. (760 mm) in diameter by 7/16 in. (11 mm) in wall thickness. The residual stress, which consists of tension on the inner surface and compression on the outer surface of the weld area, was determined using the Gunnert technique.

34. Watanabe, M., S. Minehisa, and H. Onoue, 1955, Some Experimental Studies on the Residual Stresses of Welded Pipes, *Journal of the Japan Welding Society* 24(2): 84–89 (in Japanese).
35. Burdekin, F. M., 1963, Local Stress Relief of Circumferential Butt Welds in Cylinders, *British Welding Journal* 10(9): 483–490.
36. Rybicki, E. F., P. A. McGuire, E. Merrick, and E. Wert, 1982, The Effect of Pipe Thickness on Residual Stresses due to Girth Welds, *Journal of Pressure Vessel Technology* 104(n.n.): 204–209.

ALUMINUM AND TITANIUM WELDMENTS

The distribution of residual stress in a 36 in. (914 mm) wide by 1/2 in. (13 mm) thick by 48 in. (1219 mm) long aluminum gas metal arc welded plate is shown in Figure 7.24. The results are typical of longitudinal residual stress in aluminum welds. A low level of residual stress occurs at the centerline of the weld because the weld and heat-affected zone are annealed by the welding heat. Therefore, the low-strength material relieves the stress by plastically yielding.

The distribution of residual stress in an edge-welded titanium alloy is shown in Figure 7.25. The base metal

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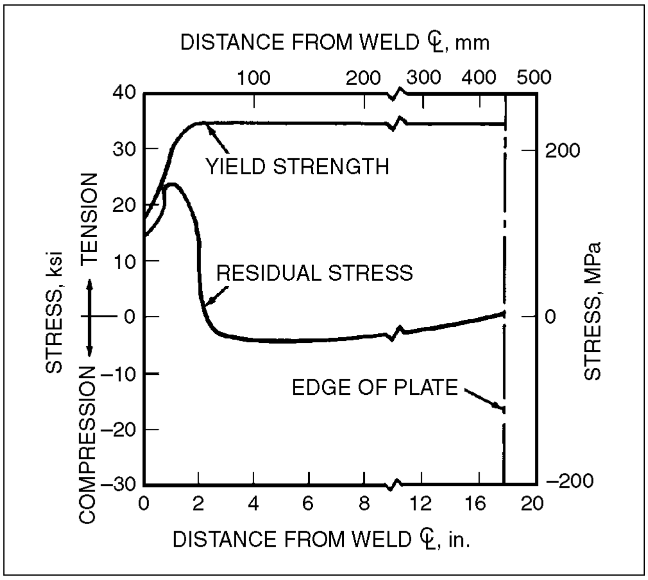

Source: Hill, H. N., 1961, Residual Stresses in Aluminum Alloys, *Metal Progress* 80(2): 92–96, Figure 1.

Figure 7.24—Distribution of Yield Strength and Longitudinal Residual Stress in an Aluminum Alloy Weldment

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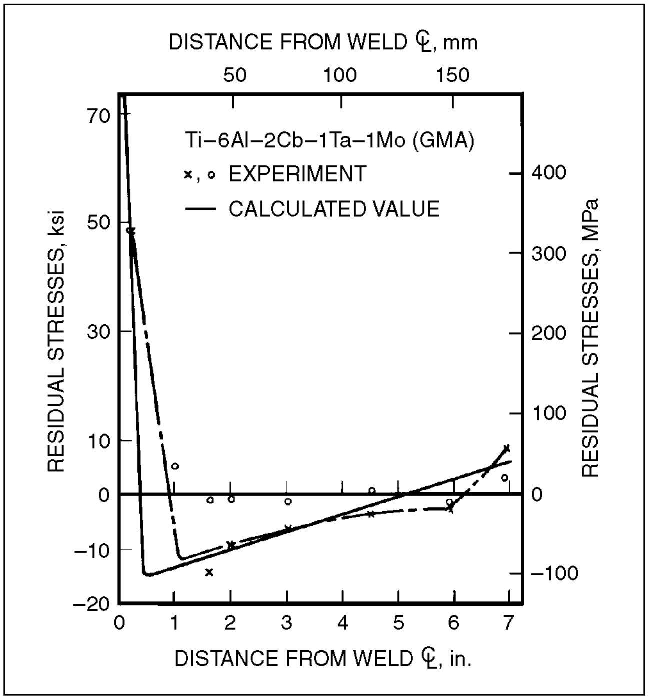


Sources: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.35; data from Hwang, J. S., 1976, Residual Stress in High-Strength Steels, M. S. thesis, Massachusetts Institute of Technology.

Figure 7.25—Distribution of Residual Stress in a Titanium Alloy Weldment

is 56 in. (1422 mm) long by 7.5 in. (191 mm) wide by 1/2 in. (12.7 mm) thick. It has been welded on one edge using the gas metal arc welding process. The experimental results agree reasonably well with the analytical predictions and may therefore be considered typical for titanium alloys.

EFFECTS OF SPECIMEN SIZE AND WEIGHT ON RESIDUAL STRESS

When studying residual stress in a welded specimen, it is important that the specimen be large enough to contain a level of residual stress that is as high as that contained in the actual structure.

EFFECT OF SPECIMEN LENGTH

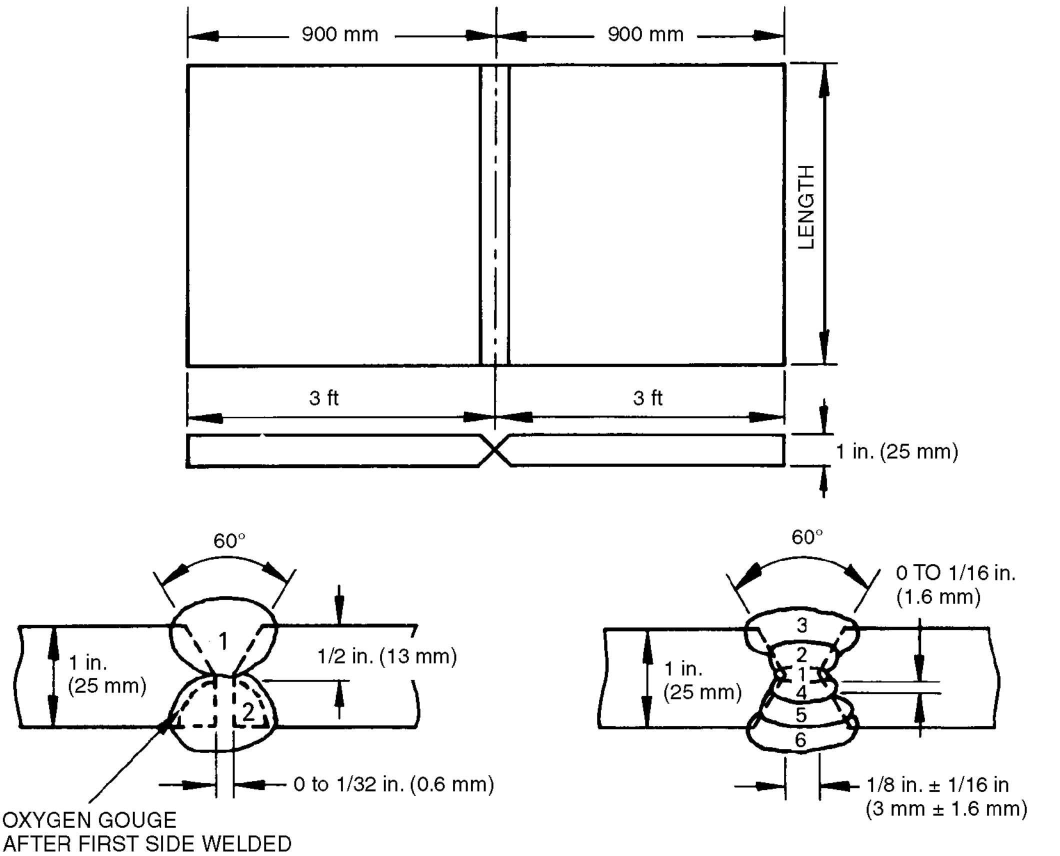
In an investigation designed to study the effect of weld length on residual stress in unrestrained low-carbon steel welded butt joints, two series of welds were prepared by the submerged arc and the shielded metal arc processes.[37] The welding conditions are summarized in Figure 7.26.

In each series of welds, the only variable was the length of the weld, as given in Figure 7.27. The width of each specimen was sufficient to ensure that full restraint was applied. Figure 7.27 depicts the distribution of the longitudinal and transverse residual stress along the welds made using the submerged arc welding and shielded metal arc welding processes.

Longitudinal residual stress must be zero at both ends of the welds, while high tensile stress exists in the central regions of the welds. The peak stress in the central region increases with increasing weld length. This effect is illustrated clearly in Figure 7.28, in which the peak stress for each panel is plotted versus the weld length. This figure indicates that welds longer than 18 in. (457 mm) must be made to produce the maximum residual tensile stress in the longitudinal direction. Longitudinal residual stress becomes uniform in the central region for welds longer than 18 in. (457 mm).

With respect to the transverse residual stress, which is shown in Figure 7.26, the stress was tensile in central areas and compressive in areas near the plate ends. The weld length had little effect on the maximum tensile stress in the central area or on the maximum stress in areas near the ends of the plate.

37. DeGarmo, E. P., J. L. Meriam, and F. Jonassen, 1946, The Effect of Weld Length upon the Residual Stresses of Unrestrained Butt Welds, *Welding Journal* 25(8): 485-s–486-s.



DETAIL SHOWS PASSES ONE AND TWO

(A) Submerged Arc Process

DETAIL SHOWS PASSES ONE THROUGH SIX

(B) Shielded Metal Arc Process, (Double-V)

Electrode:	EH14 1/4 in. (6 mm) F62-EH14-200	
Voltage:	32	
Current:	1050 A	
Speed of Arc Travel:	~12.5 in./min (~5.2 mm/s)	
Details:	Pass 1:	Oxygen Gouge Back Side
	Pass 2:	

Electrode:	Passes 1 and 4:	5/32 in. (4 mm) E6010
	Passes 2, 3, 5, and 6:	1/4 in. (6 mm) E6012
Current:	Root Passes:	150–165 A
Details:	Passes 1–3:	BACK CHIP
	Passes 4–6:	

Sources: Adapted from DeGarmo, E. P., J. L. Meriam, and F. Jonassen, 1946, The Effect of Weld Length upon the Residual Stresses of Unrestrained Butt Welds, *Welding Journal* 25(8): 485-s–486-s, Figure 1; and Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.39.

Figure 7.26—Welding Conditions for the Residual Stress Measurements Shown in Figures 7.27 and 7.28: (A) Submerged Arc Process and (B) Shielded Metal Arc Process (Double-V)

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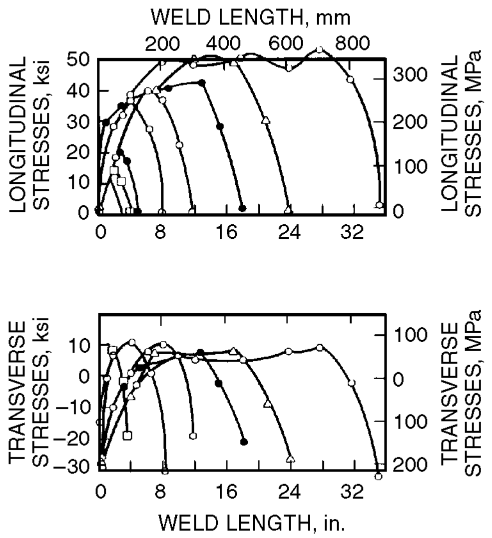
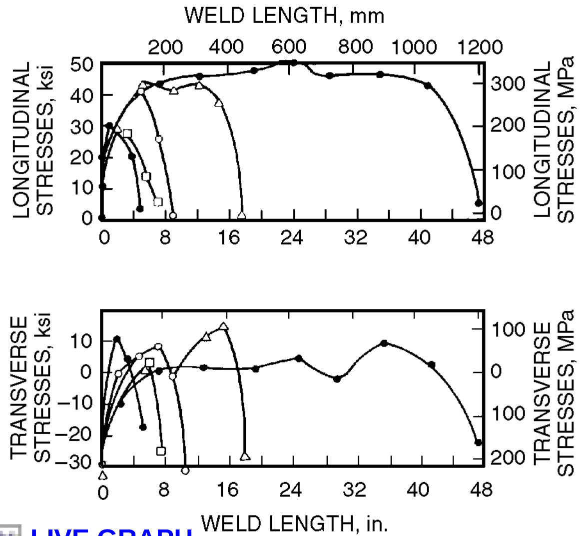


(A) Submerged Arc Welds



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(B) Shielded Metal Arc Welds

Sources: DeGarmo, E. P., J. L. Meriam, and F. Jonassen, 1946, The Effect of Weld Length upon the Residual Stresses of Unrestrained Butt Welds, *Welding Journal* 25(8): 485-s–486-s, Figures 2 and 3; and Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.40.

Figure 7.27—Effect of Length on Residual Stress Distribution in Weldments: (A) Submerged Arc Welds and (B) Shielded Metal Arc Welds

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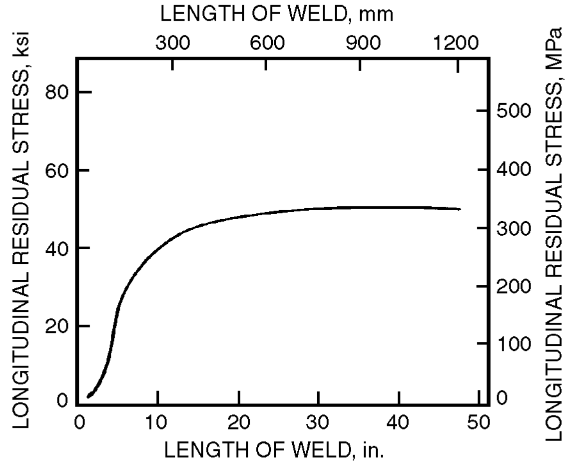


Sources: DeGarmo, E. P., J. L. Meriam, and F. Jonassen, 1946, The Effect of Weld Length upon the Residual Stresses of Unrestrained Butt Welds, *Welding Journal* 25(8): 485-s–486-s, Figure 4; and Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.41.

Figure 7.28—Effect of the Length of the Weld on Maximum Residual Stress

Residual stress distributions were similar in welds made by means of both the submerged arc and the shielded metal arc processes. Smooth stress distributions were obtained in welds made by the submerged arc process, while stress distributions in welds made by the shielded metal arc process were somewhat uneven.[38]

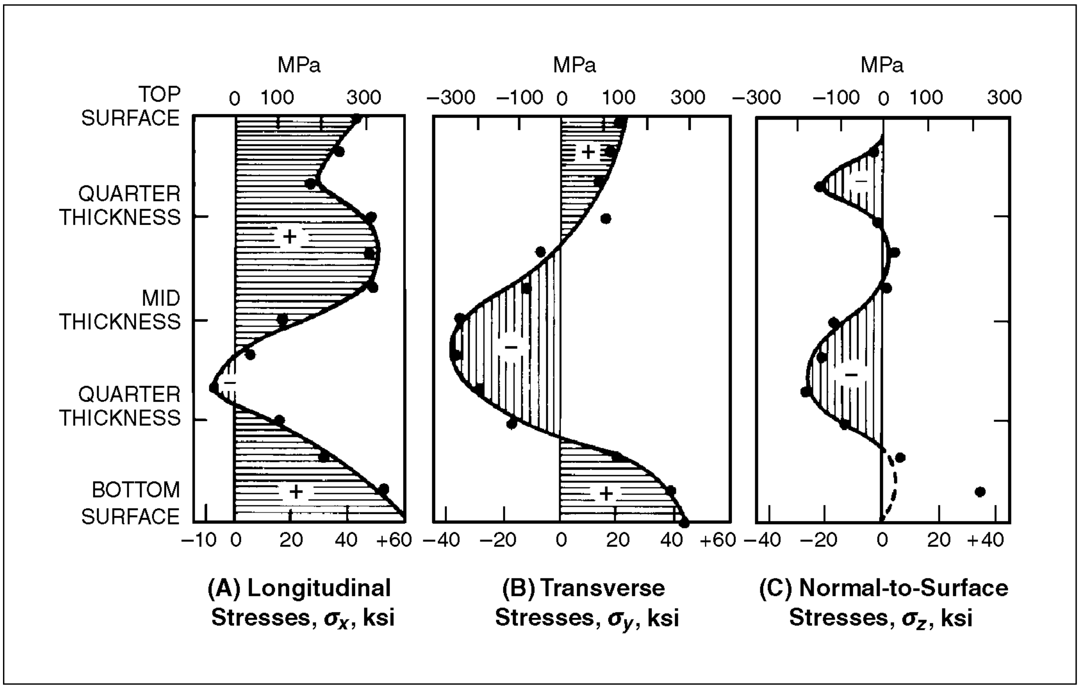
EFFECT OF SPECIMEN WIDTH

Compared with the effect of specimen length, the effect of specimen width on residual stress is minimal, as long as the specimen is sufficiently long. In fact, the effect of specimen width is negligible when the width is greater than several times the width of the weld and heat-affected zones.

RESIDUAL STRESS IN HEAVY WELDMENTS

When a weldment is made in plate more than 1 in. (25 mm) thick, residual stress can vary significantly

38. See Reference 37.



Source: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.42; Gunnert, R., 1958, Method for Measuring Tri-Axial Residual Stresses, *Welding Research Abroad* 4(10): 17–25.

Figure 7.29—Distribution of Longitudinal, Transverse, and Short Transverse Residual Stress Through the Thickness of a 1 in. (25 mm) Thick Steel Plate: (A) Longitudinal Stress, σ_x, ksi (MPa); (B) Transverse Stress, σ_y, ksi (MPa); and (C) Normal-To-Surface Stress, σ_z, ksi (MPa)

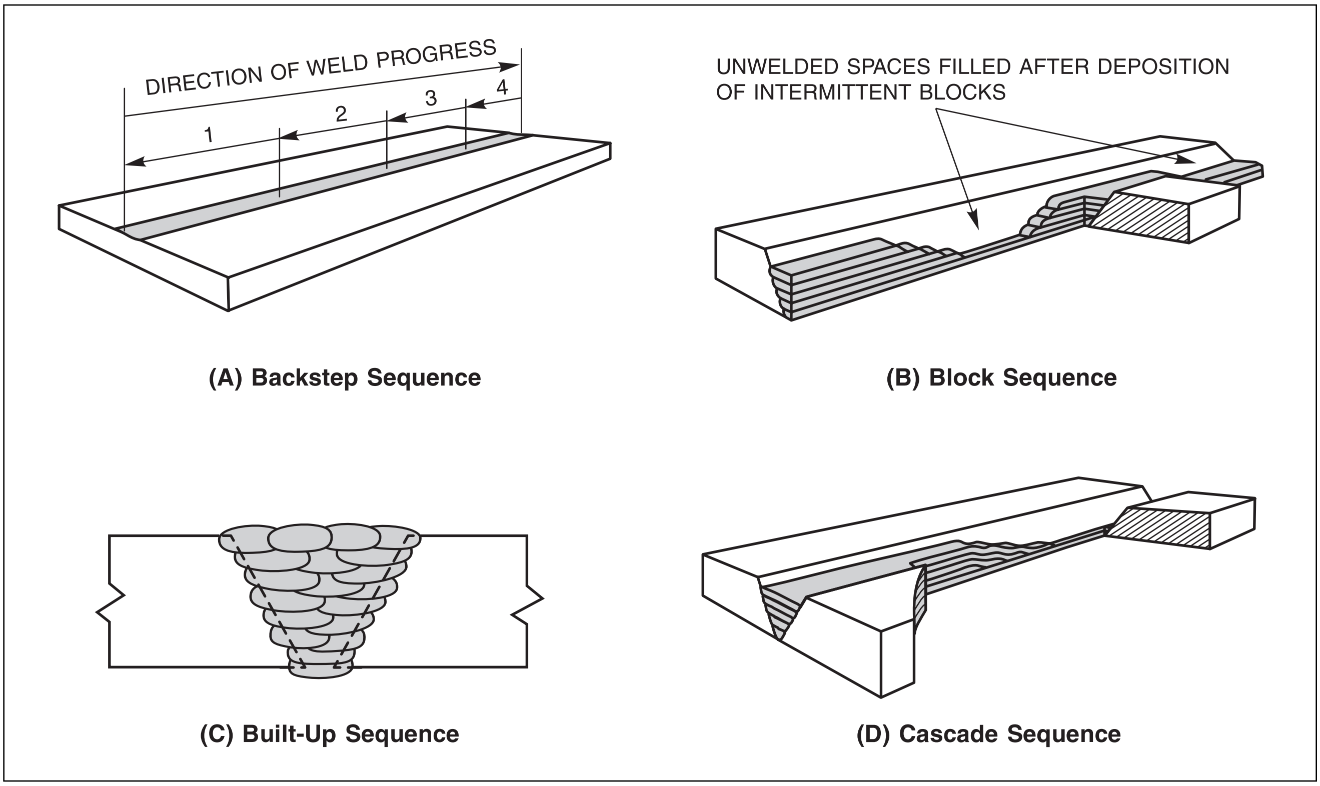
through the plate thickness.[39] Figure 7.29 illustrates the distribution of residual stress in the three directions in the weld metal of a butt joint 1 in. (25 mm) thick in low-carbon steel plates. In a study, Gunnert made welds with covered electrodes 1/8 in. to 3/16 in. (3 mm to 5 mm) in diameter. Welding was sequenced alternately on both sides so that angular distortion would be minimized. Residual stress measurements were obtained using the Gunnert technique.[40]

As shown in Figures 7.29(A) and (B), both the longitudinal and transverse stresses were tensile in areas near both surfaces of the weld. Compressive stress in the interior of the weld apparently was produced during the welding of the top and bottom passes. Figure 7.29(C) shows the distribution of stresses, σ_z, normal to the plate surface. At both surfaces, σ_z must be zero. The residual stress was primarily compressive below the surface.

39. See Reference 25.
40. See Reference 25.

EFFECTS OF WELDING SEQUENCE ON RESIDUAL STRESS

When welding a long butt joint, various types of welding sequences—including the backstep, block, build-up, and cascade sequences—can be used in an attempt to reduce residual stress and distortion. The selection of the proper welding sequence is important, especially when welding joints with high restraint, such as repair welds. These welding sequences are shown in Figure 7.30.



Source: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.46.

Figure 7.30—Welding Sequences Used to Reduce Welding Stress and Distortion

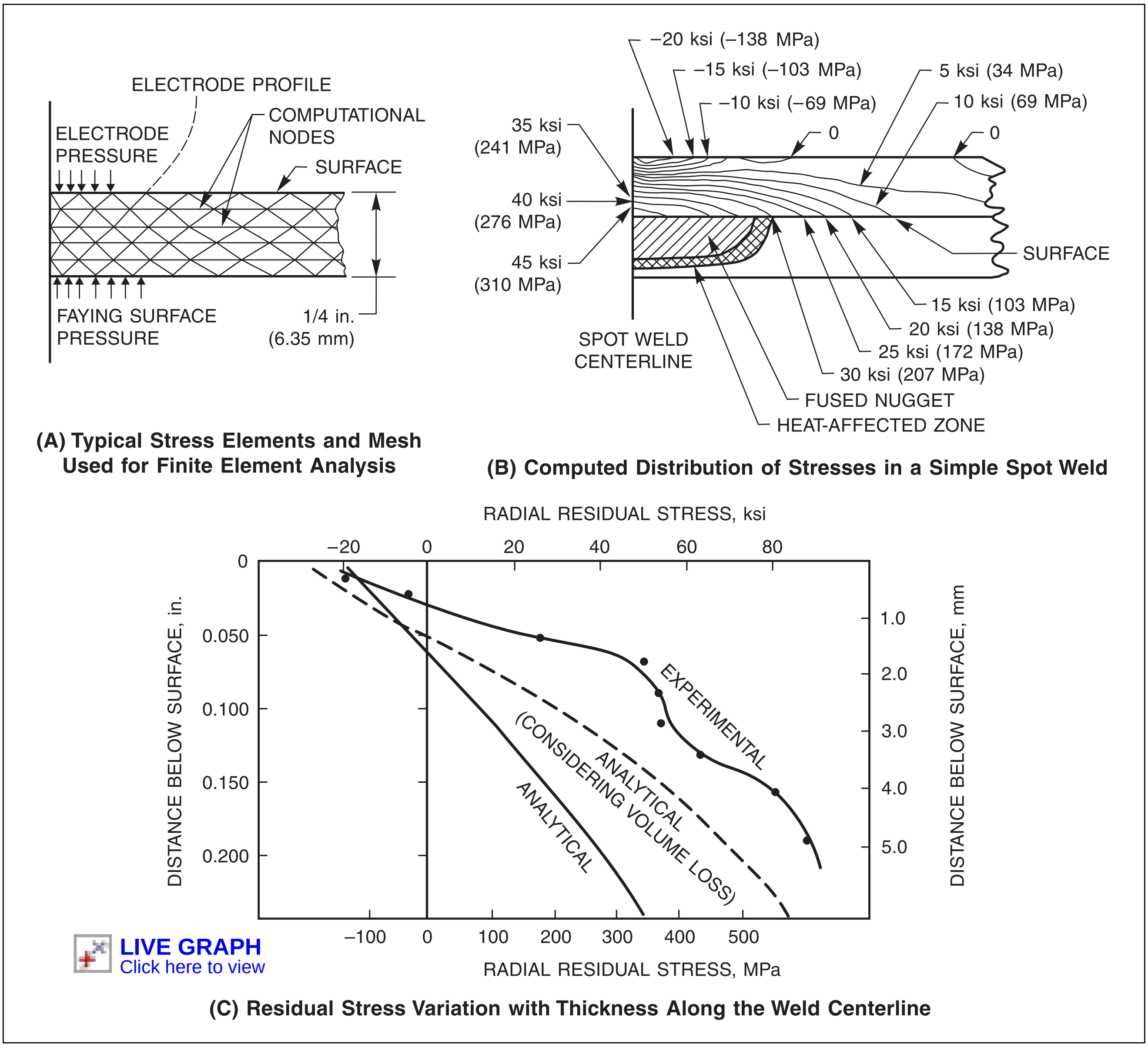
The effects of welding sequence on residual stress and shrinkage in restrained butt welds and circular patch welds can be summarized as follows:[41]

1. Welding sequence has little effect on residual stress along the weld; however, longitudinal tensile stress is likely to be relatively high;
2. Differences in welding sequence can result in considerable differences in transverse shrinkage, the total elastic energy stored in restrained joints, and reaction stress in the inner plates of circular welds; and
3. Block welding generally results in less shrinkage, strain energy, and reaction stress than do multilayer sequences.

RESIDUAL STRESS IN WELDS MADE WITH DIFFERENT WELDING PROCESSES

It is likely that the distributions of residual stress are similar in welds made utilizing various processes, including the shielded metal arc, submerged arc, gas metal arc, and gas tungsten arc processes. For example, Figures 7.27(A) and (B) demonstrate that the residual stress in the welds made with shielded metal arc welding and submerged arc welding are similar. However, this is true when the design and relative size of the weldments are similar. When the joint design and weld size are significantly different, the magnitude and distribution of the residual stress may also change.

41. Kihara, H., M. Watanabe, K. Masubuchi, and K. Satoh, 1959, Researches on Welding Stress and Shrinkage Distortion in Japan, Vol. 4 of *60th Anniversary Series of the Society of Naval Architects of Japan*, Tokyo: Society of Naval Architects of Japan; Jonassen, F., J. L. Meriam, and E. P. DeGarmo, 1946, Effect of Certain Block and Other Special Welding Procedures on Residual Welding Stresses, *Welding Journal* 25(9): 492-s–496-s; Weck, R., 1947, *Transverse Contractions and Residual Stresses in Butt Welded Mild Steel Plates*, Report R4, London: Admiralty Ship Welding Committee; and Kihara, H., K. Masubuchi, and Y. Matsuyama, 1957, *Effect of Welding Sequence on Transverse Shrinkage and Residual Stresses*, Report No. 24, Tokyo: Transportation Technical Research Institute.



Source: Adapted from Lindh, D. V. and J. L. Tocher, 1967, Heat Generation and Residual Stress Development in Resistance Spot Welding, *Welding Journal* 46(8): 351-s–360-s, Figures 7, 9, and 10.

Figure 7.31—Residual Stresses in a Single Spot Weld

As stated earlier, residual stresses are produced during many manufacturing processes that produce an uneven distribution of nonelastic strains, including thermal and plastic strains. For example, flame heating and cutting cause residual stresses similar to those produced by arc welding. Resistance welding processes also produce residual stresses. Presented here are results obtained by Lindh and Tocher on heat generation and residual stress development in resistance welding of titanium 8Al-1Mo-1V alloy sheets 1/4 in. (6.4 mm) thick.[42] Figure 7.31(A) illustrates the typical stress elements and mesh used for a finite element analysis, while Figure 7.31(B) shows the computed distribution of stresses in a single spot weld.

Residual stresses were determined by measuring the change in surface strains adjacent to the edge of a hole

42. Lindh, D. V., and J. L. Tocher, 1967, Heat Generation and Residual Stress Development in Resistance Spot Welding, *Welding Journal* 46(8): 351-s–360-s.

Table 7.4
Weld Schedules, Heat Generation, and Residual Heat for Sample Spot Welds

Setting Number	Weld Schedule			Phase Angle Setting	Heat Generated (Btu [103 J])	Heat to Electrodes (Btu [103 J])	Residual Heat (Btu [103 J])	Summation of Heat (Btu [103 J])
	Cool Cycles	Heat Cycles	Impulses					
1	0.5	5	20	25*	25.8† (27.2)	11.4 (12.0)	10 (10.5)	+4.4 (+4.6)
2	0.5	5	24	55	18.0 (19.0)	10.0 (10.5)	10 (10.5)	–2.0 (–2.1)
3	2.5	5	40	67	23.0 (24.2)	—	10 (10.5)	—
4	4.5	5	50	52	28.7 (30.2)	14.3 (15.1)	10 (10.5)	+4.4 (+4.6)

*Machine set on parallel. All other welds made in series.
† 1 Btu = 1.054 × 103 J

Source: Adapted from Lindh, D. V., and J. L. Tocher, 1967, Heat Generation and Residual Stress Development in Resistance Spot Welding, *Welding Journal* 46(8): 351-s–360-s, Table 1.

as the depth of the hole was increased by drilling. Figure 7.31(C) shows residual stress variation with thickness along the weld centerline. High tensile residual stresses were produced in regions near the joint surface, while compressive residual stresses were produced in regions near the outer surface. It was found that changes in the weld schedule had little effect on the residual stress patterns. Table 7.4 presents weld schedules, heat generation and loss, and residual heat for sample spot welds.

WELD DISTORTION

The distortion found in fabricated structures is caused by three fundamental dimensional changes that occur during welding: (1) transverse shrinkage that occurs perpendicular to the weld line, (2) longitudinal shrinkage that occurs parallel to the weld line, and (3) an angular change that consists of rotation around the weld line. These dimensional changes are illustrated in Figure 7.32.

Figure 7.32(A) demonstrates transverse shrinkage in a simple welded butt joint. The distribution of the longitudinal residual stress, σ_x, discussed earlier, is shown again in Figure 7.32(B). This stress causes longitudinal shrinkage. This shrinkage of the weld metal and base metal regions adjacent to the weld is restrained by the surrounding base metal. Figure 7.32(C) depicts the angular change that occurs in a butt joint. The nonuniformity of the transverse shrinkage in the thickness direction causes this rotation. Figure 7.32(D) shows the angular change that occurs in a fillet weld. Here, the angular change is caused by the unbalance of shrinkage on opposite sides of the flange member.

The shrinkage and distortion that occur during the fabrication of actual structures are far more complex than illustrated in Figure 7.32. When longitudinal shrinkage occurs in a fillet welded joint, the joint bends longitudinally unless the weld line is located along the neutral axis of the joint. Whether or not a joint is constrained externally also affects the magnitude and form of the distortion.

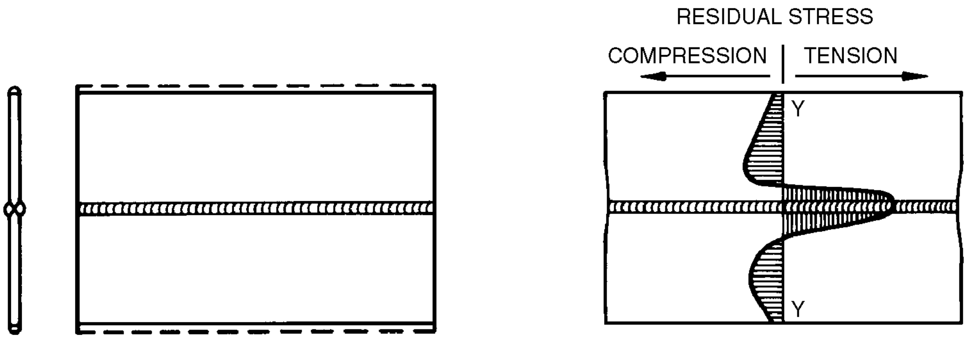
TRANSVERSE SHRINKAGE

In this section, a discussion is presented of transverse shrinkage in a butt joint, considering the effects of nonuniform restraint and multipass welding. A brief discussion is then presented of transverse shrinkage in a fillet joint.

Butt Joints

Several formulas have been proposed to estimate the amounts of transverse shrinkage in butt welds.[43] To cite

43. Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press; Masubuchi, K., 1974, *Residual Stresses and Distortion in Welded Aluminum Structures and their Effects on Service Performance*, Welding Research Council Bulletin 174, New York: Welding Research Council; Masubuchi, K. 1970, *Control of Distortion and Shrinkage in Welding,* Welding Research Council Bulletin 149, New York: Welding Research Council; Sprargen, W., and W. G. Ettinger, 1950a, Shrinkage Distortion in Welding, *Welding Journal* 29(6): 292-s–294-s; and Sprargen, W., and W. G. Ettinger, 1950b, Shrinkage Distortion in Welding, *Welding Journal* 29(7): 323-s–335-s.



(A) Transverse Shrinkage in a Butt Joint

(B) Longitudinal Shrinkage in a Butt a Joint (Distribution of Longitudinal Residual Stress, σ_x, is Also Shown)

(C) Angular Change in a Butt Joint

(D) Angular Change in a Fillet Weld

Note: Figure 7.30 shows the distribution of the longitudinal residual stress, σ_x, along the transverse section Y-Y.

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Figure 7.32—Fundamental Dimensional Changes that Occur in Weldments: Transverse Shrinkage in a Butt Joint; (B) Longitudinal Shrinkage in a Butt Joint (Distribution of Longitudinal Residual Stress, σ_x, Is Also Shown); (C) Angular Change in a Butt Joint; and (D) Angular Change in a Fillet Weld

one example, Spraragen and Ettinger suggest that the amount of transverse shrinkage in carbon and low-alloy steel welds can be estimated using the following equation:[44]

$$S = 0.2\frac{A_w}{t} + 0.05\ d \qquad (7.11)$$

where

S = Transverse shrinkage, in. (mm);
A_w = Cross-sectional area of weld, in.^{2} (mm^2);
t = Thickness of plates, in. (mm); and
d = Root opening, in. (mm).

According to Spraragen and Ettinger, this formula is particularly applicable to plate thicker than 1 in. (25.4 mm).[45] If the plate is thinner than 1 in. (25.4 mm), the value of the coefficient (0.2) should be changed to 0.18, as the plate does not absorb as much heat.

However, the transverse shrinkage that occurs in welded butt joints in actual structures is usually much more complex for the following reasons:

1. Rotational distortion,
2. Nonuniform joint restraint, and
3. Multipass welding.

These are discussed in more detail below.

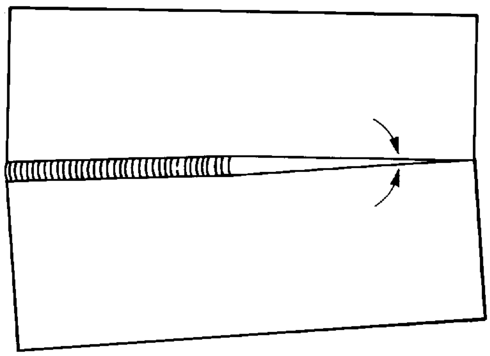
44. Sprargen, W., and W. G. Ettinger, 1950a, Shrinkage Distortion in Welding, *Welding Journal* 29(6): 292-s–294-s and Spraragen, W., and W. G. Ettinger, 1950b, Shrinkage Distortion in Welding, *Welding Journal* 29(7): 323-s–335-s.

45. See Reference 44.

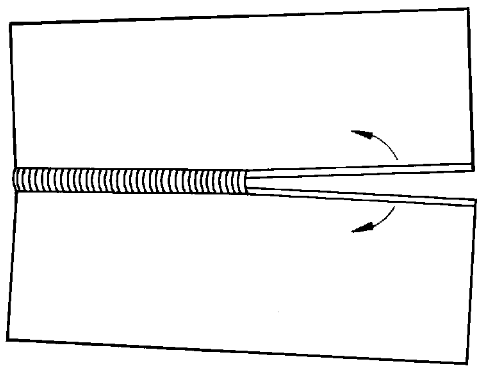
Rotational Distortion. Since much fusion welding is performed as the heat source travels from one end of a joint to the other end, unwelded portions of the joint move as the welding operation progresses, causing rotational distortion. When two free plates are butt welded, the unwelded portions of the joint either close, as shown in Figure 7.33(A), or open, as shown in Figure 7.33(B).

These distortional phenomena can be explained by Figure 7.10, which illustrates the time change of the center deflection of a metal bar under the influence of a longitudinal moving heat source. If the deformations in the unwelded portions of the joint are similar to those beyond Point B, the finishing ends of the joint will close. This phenomenon frequently occurs during the welding of steel plates using the shielded metal arc process. On the other hand, if deformations in regions near the welding arc start to close at Point A (or somewhere between Points O and B), the finishing end of the joint will open. This phenomenon frequently occurs during the welding of steel plates using the gas metal arc and submerged arc processes, resulting in a number of difficulties.

Tack welds are typically used to minimize rotational distortion in butt welds. In the case of manual welding, tack welds can easily be made. When automated welding processes are used, however, a welder must be contracted to perform the tack welds, incurring additional costs. Special care must be taken to melt the tack welds completely during the subsequent welding operation. Another difficulty is that tack welds often break due to the thermal stresses caused by welding. Engineers working in Japanese shipyards experienced the cracking of tack welds when performing one-sided submerged arc welding. They found that the use of large tack welds (up to 12 in. [305 mm] long) prevented the cracking of tack welds at the finishing end ahead of the arc.



(A) Unwelded Protion of the Joint Closes
(in Shielded Metal Arc Welds)



(B) Unwelded Portion of the Joint Opens
(Submerged Arc Welds)

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Figure 7.33—Rotational Distortion in a Butt Joint: (A) Shielded Metal Arc Weld and (B) Submerged Arc Weld

Joint Restraint. The amount of transverse shrinkage that occurs in welds is affected by the degree of restraint applied to the joint. External restraint acts like a system of transverse springs. The degree of restraint is expressed by the rigidity of the system of springs. The amount of shrinkage decreases as the degree of restraint increases. For a number of joint types, the restraint is not uniform along the joint.

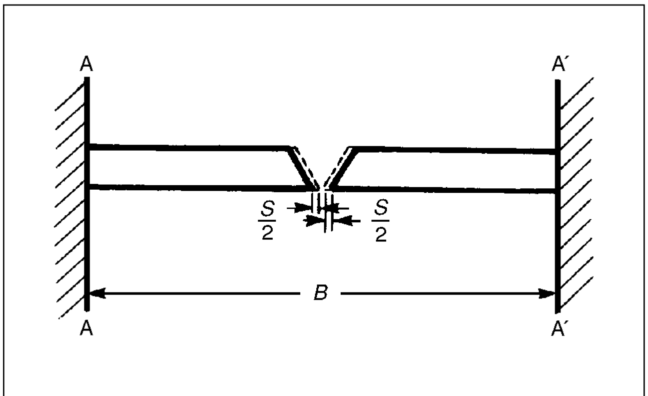
In order to study quantitatively the effect of joint restraint on transverse shrinkage in welded butt joints, it is first necessary to define analytically the degree of restraint of the butt joint. As a simple example, Figure 7.34 depicts a butt joint fixed by two walls, A-A and A′-A′, so that the joint width, *B*, remains unmoved during welding.

When transverse shrinkage occurs, it causes reaction stress, as follows:

$$\sigma = E\left(\frac{S}{B}\right) \tag{7.12}$$

where

σ = Reaction stress, ksi (MPa);
E = Modulus of elasticity, ksi (MPa);
S = Transverse shrinkage, in. (mm); and
B = Width of the joint, in. (mm).



Source: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 6.20.

Figure 7.34—Definition of the Degree of Restraint, k_s, of a Simple Butt Joint

The degree of restraint of the joint, k_s, is defined as the amount of reaction stress caused by the amount of transverse shrinkage in the unit. This can be expressed as follows:

$$k_s = \frac{\sigma}{S} = \frac{E}{B} \tag{7.13}$$

where

k_s = Degree of restraint of the joint, ksi/in. (MPa/mm);
σ = Reaction stress, ksi (MPa);
S = Transverse shrinkage, in. (mm);
E = Modulus of elasticity, ksi (MPa); and
B = Width of the joint, in. (mm).

By definition, joint restraint has the dimension of ksi/in. (MPa/mm). Joint restraint is also inversely proportional to the size of deformable portions of the joint, B. For example, when the distance between the fixed points A-A and A′-A′ is increased from B to $2B$, the degree of restraint decreases by one-half.

Several investigators have used various types of welded joints to investigate the effects of the degree of restraint on transverse shrinkage in a butt weld. Figure 7.35 presents definitions for the degree of restraint in three types of butt joints—the circular-ring type used by Kihara and Masubuchi,[46] the slit-type used by Kihara, Masubuchi, and Matsuyama,[47] and the H-type constraint specimens used by Naka.[48] By using the ratio of transverse shrinkage of restrained joints and a free (unrestrained) joint, it is possible to compare the shrinkage values obtained by different investigators using different joints.[49]

For the circular-ring type shown in Figure 7.35(A), the following expression is used:

$$k_s = \frac{E}{4\pi} \cdot \frac{1}{b-a} \left(LOG_e \frac{b}{a} - \frac{b^2 - a^2}{b^2 + a^2} \right) \tag{7.14}$$

where

k_s = Degree of restraint of the joint, ksi/in. (MPa/mm);
E = Modulus of elasticity, ksi (MPa);
π = 3.1416
b = Outer radius of the ring-type specimen, in. (mm); and
a = Inner radius of the ring-type specimen, in, (mm).

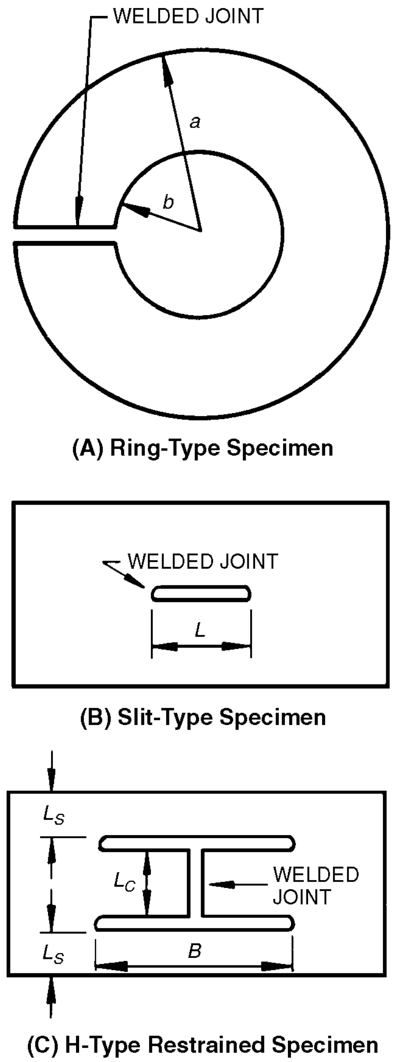
The equation used for the slit-type specimen shown in Figure 7.35(B) is as follows:

$$k_s = \frac{2E}{\pi L} \tag{7.15}$$

where

k_s = Degree of restraint of the joint, ksi/in. (MPa/mm);
E = Modulus of elasticity, ksi (MPa);
π = 3.1416; and
L = Distance between stiffeners, in. (mm).

46. Kihara, H., and K. Masubuchi, 1956, *Studies on the Shrinkage and Residual Welding Stress of Constrained Fundamental Joint. Part II: Effect of Combination of Welding Direction, Chipping, and Flame Gouging, Root Distance, Type of Bevel, and Other Welding Procedures on Transverse Shrinkage*, Report No. 20. Tokyo: Transportation Technical Institute; Kihara, H., and K. Masubuchi, 1953, *Studies on the Shrinkage and Residual Welding Stress of Constrained Fundamental Joint. Part I: Effects of Root Diameter, Welding Direction, Weaving Motion, and Type of Electrode on Transverse Shrinkage*, Report No. 7. Tokyo: Transportation Technical Institute.
47. Kihara, H., K. Masubuchi, and Y. Matsuyama, 1957, *Effect of Welding Sequence on Transverse Shrinkage and Residual Stresses*, Report No. 24. Tokyo: Transportation Technical Research Institute.
48. Naka, T., 1950, *Shrinkage and Cracking in Welds*, Tokyo: Komine Publishing.
49. Please note that these joints are used for experimental purposes, not for practical welding construction.



Key:

- a = Inner radius of the ring-type specimen, in. (mm)
- b = Outer radius of the ring-type specimen, in. (mm)
- B = Width of the joint, in. (mm)
- L = Distance between stiffeners, in. (mm)
- L_c = 1/2 of the width of the restraining member of the H-type restrained specimen shown in Figure 7.35(C), in. (mm)
- L_s = Weld length of the H-type restrained specimen shown in Figure 7.35(C), in. (mm)

Source: Adapted from Watanabe, M., and K. Satoh, 1961, Effect of Welding Conditions on the Shrinkage Distortion in Welded Structures, *Welding Journal* 40(8): 377-s–384-s, Figure 10.

Figure 7.35—Effect of Specimen Type on the External Constraint (k_s): (A) Ring-Type Specimen; (B) Slit-Type Specimen; and (C) H-Type Restrained Specimen

For the H-type restrained specimen illustrated in Figure 7.35(C) the following is used:

$$k_s = \frac{E}{B\left(1 + \frac{L_c}{2L_s}\right)} \tag{7.16}$$

where

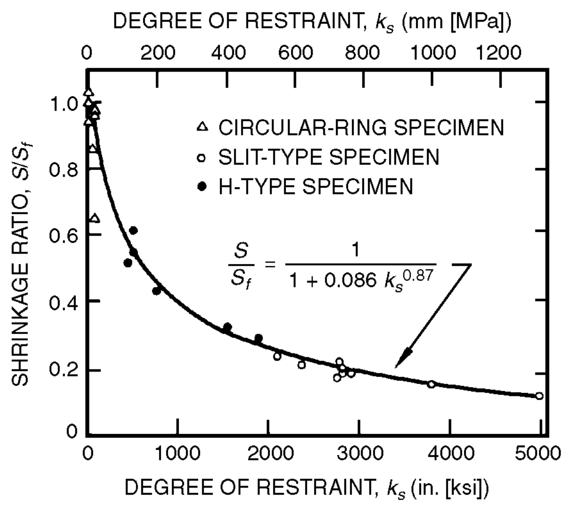
- k_s = Degree of restraint of the joint, ksi/in. (MPa/mm);
- E = Modulus of elasticity, ksi (MPa);
- B = Width of the joint, in. (mm);
- L_c = 1/2 of the width of the restraining member of the H-type restrained specimen shown in Figure 7.35(C), in. (mm); and
- L_s = Weld length of the H-type restrained specimen shown in Figure 7.35(C), in. (mm).

Watanabe and Satoh found that the values of transverse shrinkage obtained by different investigators using different types of restrained joints can be arranged on a single curve by plotting the relationship between the degree of restraint (k_s) and the ratio of the transverse shrinkage of a restrained joint (S) and the transverse shrinkage of an unrestrained joint (S_f), that is, S/S_f.[50] This is shown in Figure 7.36.

When a joint is long, changes in the degree of restraint along the joint must be considered. In the case of a slit-type specimen, for example, the degree of restraint is high in the regions near both ends of the slit, while it is rather low in the central region. Therefore, as can be observed in Figure 7.37, the amount of transverse shrinkage in the central region is high, whereas it is low in the regions near both ends. Welds similar to the slit weld are frequently made in repairs.

Multipass Welding. Welding is frequently performed in one pass, especially for thin plates. However, when welding is performed in a number of passes, particularly when welding thick plates, shrinkage is accumulated. Most transverse shrinkage that occurs in single-pass butt joints results from the contraction of the base metal. The base metal expands during welding, but when the weld metal solidifies, the expanded base metal shrinks. This accounts for a major portion of the transverse shrinkage. Shrinkage of the weld itself comprises only approximately 10% of the actual shrinkage.[51]

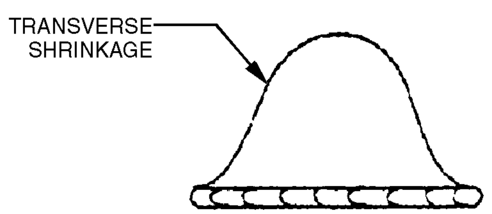
50. Watanabe, M., and K. Satoh, 1961, Effect of Welding Conditions on the Shrinkage Distortion in Welded Structures, *Welding Journal* 40(8): 377-s–384-s.
51. Naka, T., 1950, *Shrinkage and Cracking in Welds,* Tokyo: Komine Publishing; Matsui, S., 1964, Investigation of Shrinkage, Restraint Stress, and Cracking in Arc Welding, Ph. D. diss., Osaka University; and Iwamura, Y., 1974, Reduction of Transverse Shrinkage in Aluminum Butt Welds, M. S. thesis, Massachusetts Institute of Technology.



Key:
S = Transverse shrinkage of a restrained joint, in. (mm)
S_f = Transverse shrinkage of an unrestrained joint, in. (mm)
k_S = Degree of restraint of the joint, ksi/in. (MPa/mm)

Source: Adapted from Watanabe, M., and K. Satoh, 1961, Effect of Welding Conditions on the Shrinkage Distortion in Welded Structures, *Welding Journal* 40(8): 377-s–384-s, Figure 12.

Figure 7.36—Effect of External Constraint on Transverse Shrinkage in Welded Butt Joints



Note: As this figure illustrates trends only, no values are shown for the weight of the deposited metal and the amount of shrinkage.

Figure 7.37—Transverse Shrinkage in a Slit-Type Joint with a Long Weld

Figures 7.38(A) and (B) present the experimental results obtained in an investigation of butt joints in low-carbon steel.[52] The curves labeled "T" represent the temperature changes, while those labeled "S" denote the changes in transverse shrinkage. Most of the shrinkage occurs after the weldment has cooled to relatively low temperatures. This figure indicates that in thicker plate, transverse shrinkage starts earlier, but the final value of the shrinkage is smaller. It should be noted, however, that this is true only when the same amount of heat input is used regardless of the joint thickness. The welding of thicker plates normally requires more than one pass.

On the other hand, during the multipass welding of constrained butt joints in carbon steel, transverse shrinkage increases with each weld pass.[53] Figure 7.39(A) illustrates the relationship between the weight of electrode consumed per unit weld length, w, which is proportional to the cross-sectional area of the weld metal, and the transverse shrinkage, S. Shrinkage is relatively pronounced during the first weld passes but diminishes during later passes because resistance to shrinkage increases as the weld metal cross section increases. A linear relationship exists between total transverse shrinkage and the logarithm of the total weight of the weld metal deposited, as shown in Figure 7.39(B).

The equation that expresses this relationship is as follows:

$$S = S_0 + b\left(\text{Log}\, w - \text{Log}\, w_o\right) \tag{7.17}$$

where

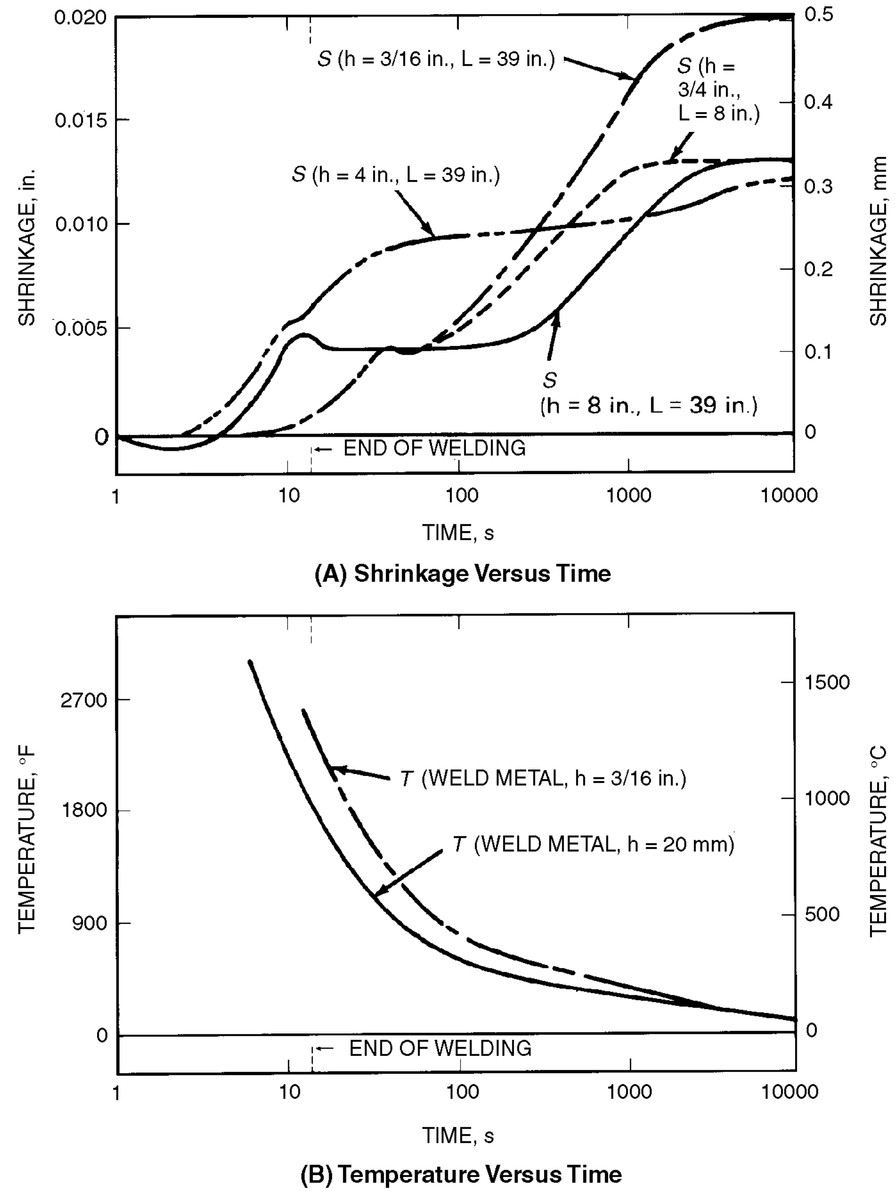
S = Total transverse shrinkage, in. (mm);
S_0 = Transverse shrinkage after first pass, in. (mm);
b = A coefficient;
w = Total weight of electrode consumed per unit weld metal, lb/in. (g/mm); and
w_0 = Weight of electrode consumed per weld length for the first pass, lb/in. (g/mm).

Figure 7.40 suggests three general principles for the reduction of transverse shrinkage. The first involves decreasing the total weight of weld metal, as shown by Line B-C. The second involves decreasing the value of tangent b in Equation (7.12), which decreases the amount of shrinkage from B to D. The third involves depositing a larger first pass, changing the shrinkage from A to A′. The amount of shrinkage after the completion of the weld thus changes from B to E.

The effects of various procedure variables on transverse shrinkage are summarized in Table 7.5. The relationship of these variables to the principles for reducing shrinkage presented above is also provided in the table. As can be observed, root opening and joint design produce the greatest effects.

52. Matsui, S., 1964, Investigation of Shrinkage, Restraint Stress, and Cracking in Arc Welding, Ph. D. diss., Osaka University.

53. See Reference 46.



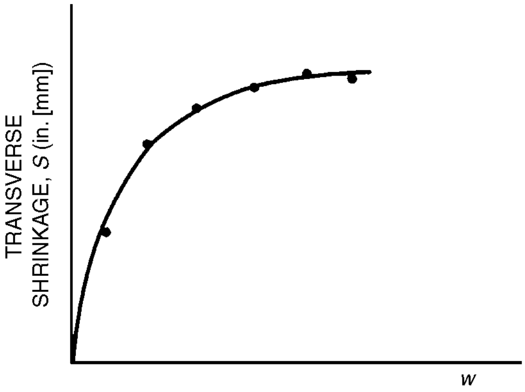
Key:

Height (h) = 3/16 in. (5 mm)		Length (L) = 39 in. (990 mm)	
h = 3/4 in. (20 mm)		L = 8 in. (200 mm)	
h = 4 in. (100 mm)		L = 38 in. (990 mm)	
h = 8 in. (200 mm)		L = 39 in. (990 mm)	

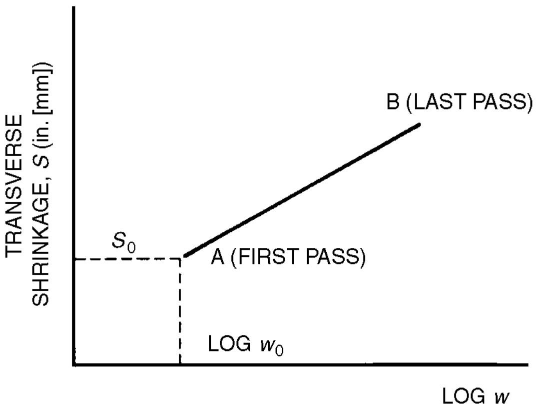
S = Transverse shrinkage, in. (mm)
T = Temperature, °F (°C)

Source: Adapted from Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 7.19.

Figure 7.38—Effect of Time on Temperature and Shrinkage: (A) Shrinkage vs. Time and (B) Temperature vs. Time



(A) Relationship Between the Weight of Electrode Consumed Per Unit Weld Length, *w*, and Transverse Shrinkage, *S*



(B) Relationship Between Log *w* and *S*

Key:

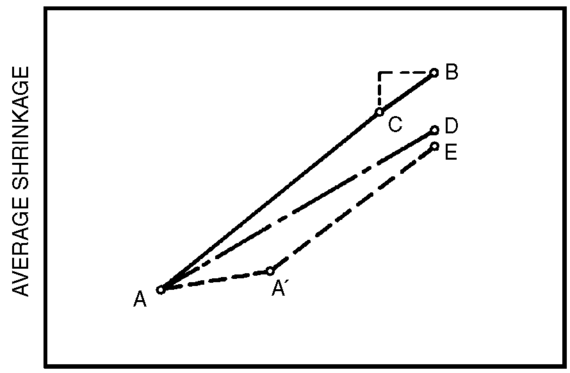
S = Total transverse shrinkage, in. (mm)

S_0 = Transverse shrinkage after the first pass, in. (mm)

w = Total weight of electrode consumed per unit weld metal, lb/in. (g/mm)

w_0 = Weight of electrode consumed per weld length for the first pass, lb/in. (g/mm)

Figure 7.39—Increase of Transverse Shrinkage in the Multipass Welding of a Butt Joint: (A) Relationship between the Weight, of Electrode Consumed per Unit Weld Length, *w*, and Transverse Shrinkage, *S*, and (B) Relationship Between Log *w* and *S*



Note: As this figure illustrates trends only, no values are shown for the weight of the deposited metal and the amount of shrinkage.

Source: Data from Kihara, H., and K. Masubuchi, 1956, *Studies on the Shrinkage and Residual Welding Stress of Constrained Fundamental Joint. Part II: Effect of Combination of Welding Direction, Chipping, and Flame Gouging, Root Distance, Type of Bevel, and Other Welding Procedures on Transverse Shrinkage*, Report No. 20. Tokyo: Transportation Technical Institute.

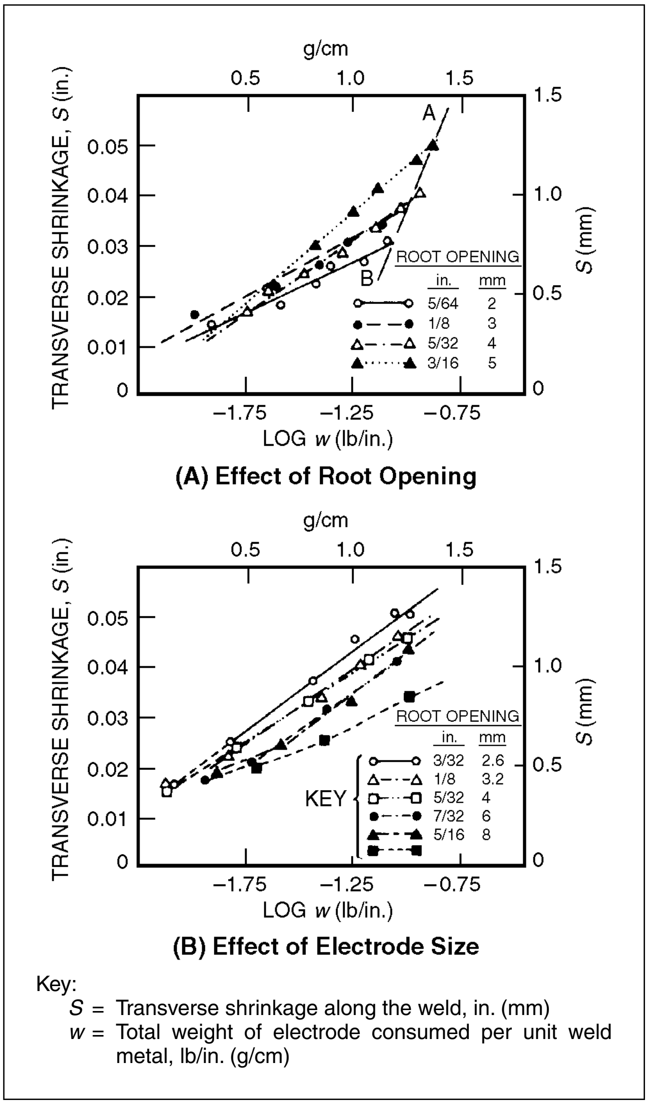
Figure 7.40—General Principles for Reducing Transverse Shrinkage

Table 7.5
Effects of Procedure Variables on Transverse Shrinkage in Butt Joints

Procedures	Effects
Root opening	Shrinkage increases as the root opening increases (see Figure 7.39). The effect is great. (Methods 1 and 2)*
Joint design	A single-V-joint produces more shrinkage than a double-V-joint. The effect is great. (Methods 1 and 2)
Electrode diameter	Shrinkage decreases when using larger-sized electrodes (see Figure 7.39). The effect is medium.
Degree of constraint	Shrinkage decreases as the degree of constraint increases. The effect is medium. (Method 2)
Electrode type	The effect is minor. (Method 2)
Peening	Shrinkage decreases as a result of peening. The effect is minor. (Method 2)

*Methods 1, 2, and 3 are shown in Figure 7.40.

Sources: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion, and Their Consequences*, New York: Pergamon Press, Table 7.7; data from Kihara, H., and K. Masubuchi, 1953, *Studies on the Shrinkage and Residual Welding Stress of Constrained Fundamental Joint. Part I: Effects of Root Diameter, Welding Direction, Weaving Motion, and Type of Electrode on Transverse Shrinkage*, Report No. 7. Tokyo: Transportation Technical Institute.



Source: Adapted from Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press, Figure 7.28.

Figure 7.41—Effect of Root Opening and Electrode Diameter on the Transverse Shrinkage of a Ring-Type Specimen (see Figure 7.32): (A) Effect of Root Opening and (B) Effect of Electrode Size

Figure 7.41(A) illustrates the effect of root opening on transverse shrinkage. As the root opening decreases, the shrinkage and the total amount of weld metal decreases. Figure 7.41(B) demonstrates the effect of electrode size on transverse shrinkage. Shrinkage decreases as the electrode size increases. However, a reduction in shrinkage cannot be obtained with large-sized electrodes unless they are also used for the first pass.

Regarding the effect of welding heat input on transverse shrinkage, shrinkage decreases as the total heat input required to weld a certain joint decreases. However, when a weld is completed in several passes, shrinkage decreases when the first pass is welded with higher heat input. In this case, an increase in shrinkage is produced after welding the first pass with a higher heat input (as can be seen when comparing Points A and A′ in Figure 7.40). However, the amount of shrinkage after the completion of the weld decreases from B to E in the same figure.

As to the effect of chipping and gouging on transverse shrinkage, removal of the weld metal by chipping produces little effect on shrinkage, and shrinkage increases due to rewelding. Since heat is applied to the weld area during oxygen gouging, shrinkage increases. It is further increased during repair welding.[54]

Fillet Welds

The amount of transverse shrinkage that occurs across a fillet weld is much smaller than that which occurs across a butt joint. The shrinkage of transverse fillet welds in carbon and low-alloy steels can be estimated using the simple formulas presented below.

The following expression can be used for T-joints with two continuous fillets:[55]

$$S = C_1\left(\frac{D_f}{t_b}\right) \tag{7.18}$$

where

S = Transverse shrinkage, in. (mm);
C_1 = 0.04 and 1.02 when S, L, and t_b are in inches and millimeters, respectively;
D_f = Fillet leg length, in. (mm); and
t_b = Thickness of the bottom plate, in. (mm).

For intermittent fillet welds, in which only portions of the joint are welded, a correcting factor of proportional length of the fillet weld to the total length of joint should be used.

54. Kihara, H., and K. Masubuchi, 1956, *Studies on the Shrinkage and Residual Welding Stress of Constrained Fundamental Joint. Part II: Effect of Combination of Welding Direction, Chipping, and Flame Gouging, Root Distance, Type of Bevel, and Other Welding Procedures on Transverse Shrinkage*, Report No. 20. Tokyo: Transportation Technical Institute.
55. Sprargen, W., and W. G. Ettinger, 1950a, Shrinkage Distortion in Welding, *Welding Journal* 29(6): 292-s–294-s and Sprargen, W., and W. G. Ettinger, 1950b, Shrinkage Distortion in Welding, *Welding Journal* 29(7): 323-s–335-s; Masubuchi, K., 1970, *Control of Distortion and Shrinkage in Welding*, Welding Research Council Bulletin 149, New York: Welding Research Council.

For fillet welds in a lap joint between plates of equal thickness (two welds), the following can be used:

$$S = C_2\left(\frac{D_f}{t_b}\right) \tag{7.19}$$

where

- S = Transverse shrinkage, in. (mm);
- C_2 = 0.06 and 1.52 when S, L, and t_b are in inches and millimeters, respectively;
- D_f = Fillet leg length, in. (mm); and
- t_b = Thickness of the bottom plate, in. (mm).

LONGITUDINAL SHRINKAGE IN BUTT JOINTS

The amount of longitudinal shrinkage that occurs in butt joints is approximately 1/1000 of the weld length. This is much less than transverse shrinkage. The following equation has been proposed for the estimation of longitudinal shrinkage in butt joints:[56]

$$\Delta L = \frac{C_3 IL}{t}10^{-7} \tag{7.20}$$

where

- ΔL = Longitudinal shrinkage, in. (mm);
- C_3 = 12 and 305 when L and t are in inches and millimeters, respectively;
- I = Welding current, A;
- L = Length of weld, in. (mm); and
- t = Plate thickness, in. (mm).

ANGULAR DISTORTION

Presented below are discussions of angular distortion in butt and fillet welds. The distortion of structural members due to the angular distortion of fillet welds is also examined.

Butt Joints

Angular change often occurs in butt joints when transverse shrinkage is not uniform in the thickness direction. Figure 7.42 presents experimental data obtained with respect to the ring-type specimens discussed above.[57] A radial groove was cut and then welded using 1/4 in. (6 mm) diameter covered electrodes. Five groove designs ranging from symmetrical double-V to single-V were used. Welding was first completed on one side. The specimen was then turned over, and the other side was backchipped and welded. The amount of angular change was measured after welding each pass. Backchipping did not affect the angular change.

Angular change in the reverse direction resulted during welding of the second side of the double-V grooves. The angular change remaining after the completion of welding depended on the ratio of weld metal deposited on the two sides of the plates. Since the angular change increased more rapidly during the welding of the second side, the minimum angular change was obtained when the first V-groove welded was slightly larger than the V-groove on the opposite side. The angular change that occurs in double-V-groove welds may be minimal when

$$\frac{t_1 + 0.5t_3}{t_1 + t_2 + t_3} = 0.6 \tag{7.21}$$

where

- t_1 = Depth of the V-groove welded first, in. (mm);
- t_2 = Depth of the V-groove welded last, in. (mm); and
- t_3 = Width of the root face, in. (mm).

Variables t_1, t_2, and t_3 are illustrated in Figure 7.42.

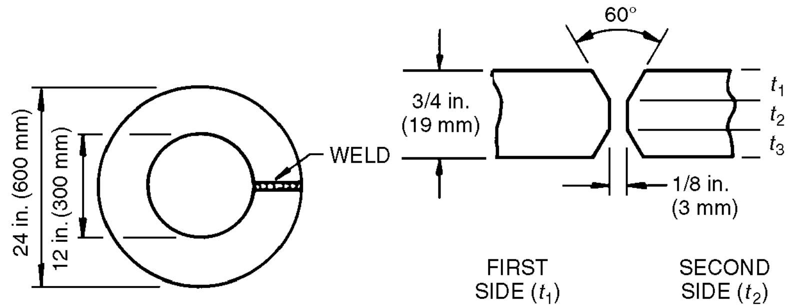
Extensive research has been conducted by the Shipbuilding Association of Japan on angular change in butt welds.[58] Figure 7.43 shows the groove shape that most successfully minimizes angular change in butt joints of various thicknesses. Curves are shown for situations with and without strongbacks in fabricating large steel plates.[59] The ordinate in this figure is expressed in terms of the ratio of the weight of deposited metal in the backing and finishing passes, w_1/w_2, which is proportional to the square of the ratio of the depth of the backing pass, h_1, and that of the finishing pass, h_2. For example, when the plate thickness is 0.75 in. (20 mm), the ratio of h_1 and h_2, which yields the minimum angular change when the joint is free, is 7 to 3. In terms of the weight of the deposited metal, the w_1/w_2 ratio is approximately 49 to 9, or a little over 5.

56. King, C. W. R., 1944, n.t. *Transactions of Institute of Engineers and Shipbuilders in Scotland* 87: 233–255; Masubuchi, K., 1970, *Control of Distortion and Shrinkage in Welding*, Welding Research Council Bulletin 149, New York: Welding Research Council.

57. See Reference 46.

58. Shipbuilding Research Association of Japan, 1959, *Researches on Welding Procedures of Thick Steel Plates Used in Construction of Large-Size Ships (Report 1)*, Tokyo: Shipbuilding Research Association of Japan (in Japanese).

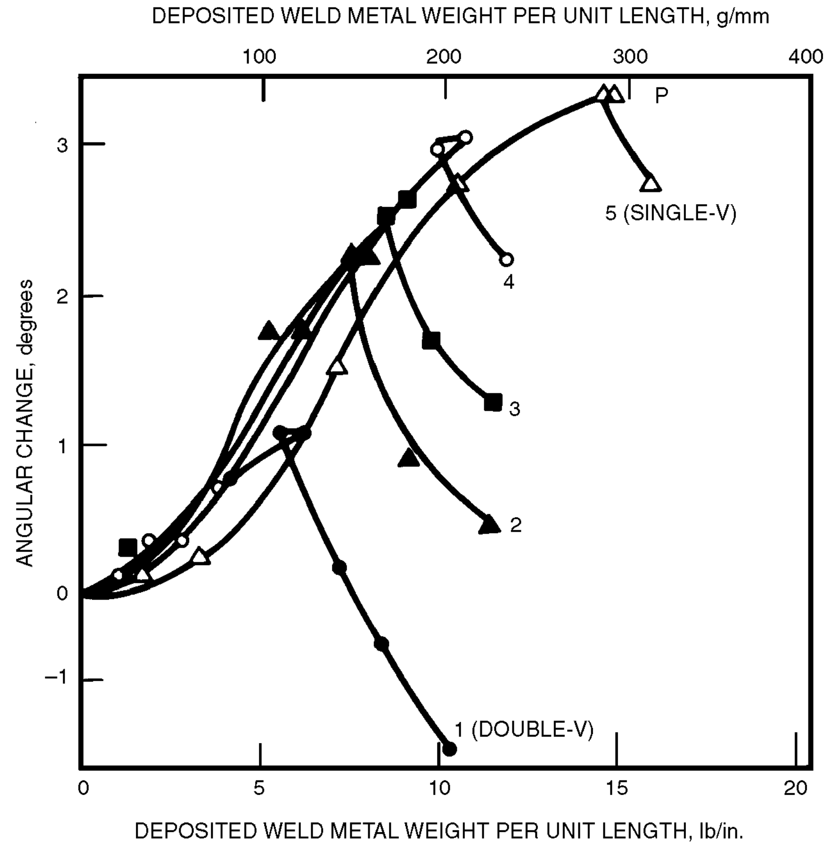
59. Strongbacks are frequently used to reduce out-of-plane distortion. The clamping shown in Figure 7.57 can be regarded as a type of strongback.



RING-TYPE SPECIMEN

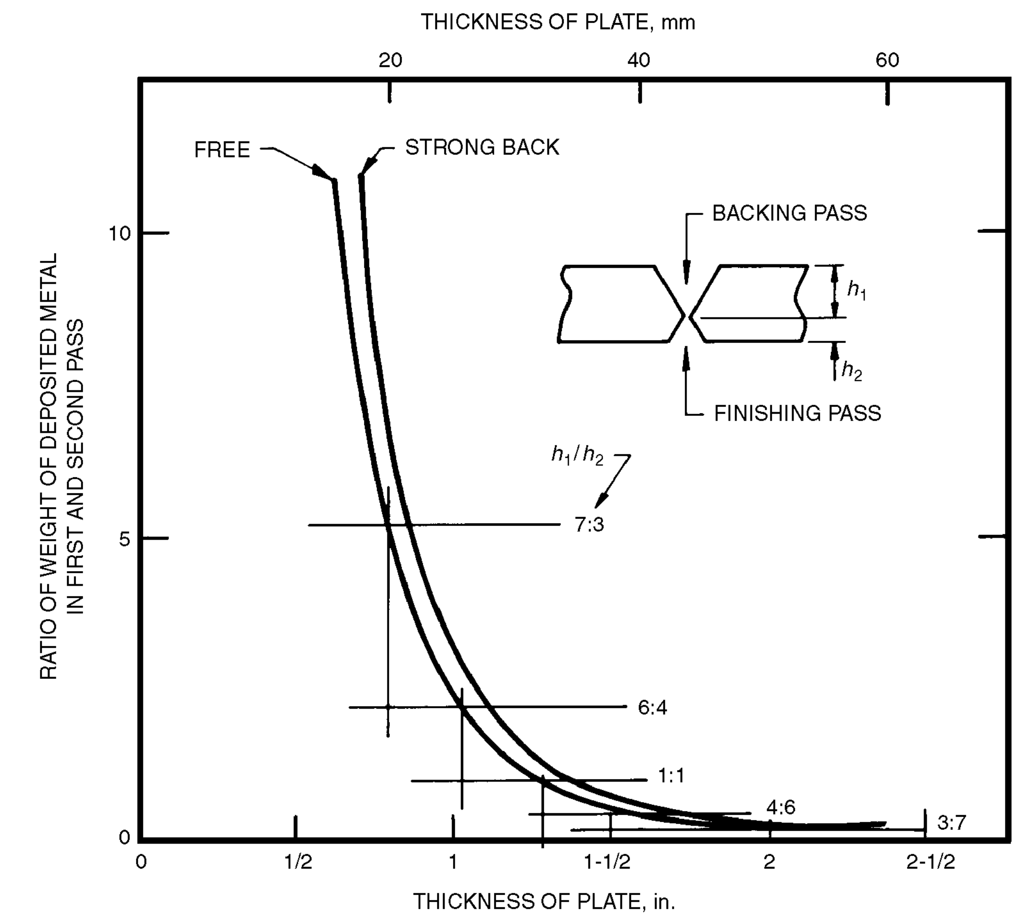
SPEC NO.	FIRST SIDE (t_1) in.	FIRST SIDE (t_1) mm	SECOND SIDE (t_2) in.	SECOND SIDE (t_2) mm
1	5/16	8.5	5/16	8.5
2	7/16	11	1/4	6
3	1/2	13	1/8	4
4	5/8	15	1/16	2
5	11/16	17	0	0

ROOT FACE (t_3) = 1/16 – 1/8 in. (2 mm)



Source: Kihara, H., and K. Masubuchi, 1956, *Studies on the Shrinkage and Residual Welding Stress of Constrained Fundamental Joint. Part II: Effect of Combination of Welding Direction, Chipping, and Flame Gouging, Root Distance, Type of Bevel, and Other Welding Procedures on Transverse Shrinkage*, Report No. 20. Tokyo: Transportation Technical Institute.

Figure 7.42—Experimental Data Gathered on Ring-Type Specimens



Key:
h_1 = Depth of the backing pass, in, (mm)
h_2 = Depth of the finishing pass, in. (mm)

Sources: Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion and Their Consequences*, New York: Pergamon Press; based on data from Shipbuilding Research Association of Japan, 1959, *Researches on Welding Procedures of Thick Steel Plates Used in Construction of Large-Size Ships (Report 1)*, Tokyo: Shipbuilding Research Association of Japan (in Japanese).

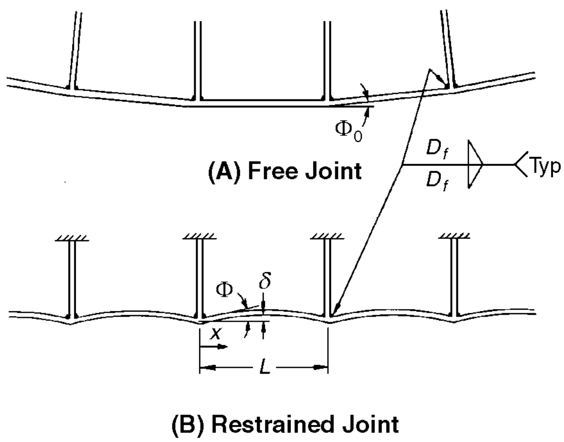
Figure 7.43—Groove Design Most Suitable to Minimizing Angular Change in Butt Joints of Various Thicknesses

Fillet Welds

If a joint is free from external restraint during fillet welding, the contraction of the weld metal causes angular distortion about the joint axis, as shown in Figure 7.44(A). However, if the members are restrained by some means, the distortion depends on the degree of restraint. For example, when the movement of stiffeners welded to a plate is prevented, the plate distorts in a wave pattern, as shown in Figure 7.44(B).

The analysis of wavy distortion and its associated stress can be handled as a problem of stress in a rigid frame.[60] In the simplest case of a uniform distortion, the relationship between angular change and distortion at the weld is expressed as follows:

60. Masubuchi, K., Y. Ogura, Y. Ishihara, and J. Hoshino, 1956, Studies on the Mechanism of the Origin and the Method of Reducing the Deformation of Shell Plating in Welded Ships, *International Shipbuilding Progress* 3(19): 123–133.



Key:

Φ_0 = Angular change in an unrestrained weld, degrees (radians)
D_f = Fillet weld leg length, in. (mm)
Φ = Angular change in a restrained joint, degrees (radians)
δ = Distortion, in. (mm)
x = Distance from the centerline of the frame to the point at which variable δ is measured, in. (mm)
L = Distance between stiffeners, in. (mm)

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Figure 7.44—Distortion Caused by Angular Change in Two Types of Fillet-Welded Structures: (A) a Free Joint and (B) a Restrained Joint

$$\frac{\delta}{L} = 0.25\ \Phi - \left[\left(\frac{x}{L}\right) - 0.5\right]^2 \Phi \tag{7.22}$$

where

Φ = Angular change in a restrained joint, degrees (radians[61]);
δ = Distortion, in. (mm);
L = Distance between stiffeners, in. (mm); and
x = Distance from the centerline of the frame to the point at which δ is measured (see Figure 7.40B), in. (mm).

When x is equal to $0.5L$, δ equals $0.25\phi\ L$ and is a maximum value. The angular change, Φ, is related to the angular change that would occur in an unrestrained weld, ϕ_0 [see Figure 7.42(A)] under the same welding conditions. Thus,

$$\Phi = \frac{\phi_0}{1 + \left(2\dfrac{R_p}{L}\right)\left(\dfrac{1}{C}\right)} \tag{7.23}$$

where

Φ = Angular change in a restrained joint, degrees (radians);
ϕ_0 = Angular change in an unrestrained weld, degrees (radians);
R_p = Rigidity of the bottom plate, ksi in.^{3} (MPa mm^3), = $Et^3/12(1 - \nu^2)$, where E denotes the modulus of elasticity, ksi (MPa); t denotes the thickness of the bottom plate, in. (mm); and ν denotes Poisson's ratio;
L = Distance between stiffeners, in. (mm); and
C = Coefficient of rigidity for angular change, lb in./in. (kg mm/mm);

The value of C in Equation (7.20) can be interpolated from Tables 7.6 and 7.7 for steel and Tables 7.8 and 7.9 for aluminum.

As noted above, rigidity, R_p, is a function of the plate thickness and the elastic constants of the material. Thus,

$$R_p = \frac{Et^3}{12\left(1 - \nu^2\right)} \tag{7.24}$$

where

R_p = Rigidity of the flange plate, ksi in.^{3} (MPa mm^3)
E = Modulus of elasticity, ksi (MPa);
t = Thickness of the flange plate, in. (mm); and
ν = Poisson's ratio.

For most metals, Poisson's ratio is approximately 0.3. Therefore, Equation (7.24) reduces to the following:

$$R_p = 0.09Et^2 \tag{7.25}$$

where

R_p = Rigidity of the flange plate, ksi in.^{3} (MPa mm^3)
E = Modulus of elasticity, ksi (MPa); and
t = Thickness of the flange plate, in. (mm).

61. One radian equals 57.3 (180/π degrees).

Table 7.6
Coefficient of Angular Rigidity, *C*, for Low-Carbon Steel
(U.S. Customary Units)

Fillet Weld Size, D_f	Weight of Electrode Consumed per Unit Weld Length, w*	Logarithm of Electrode Weight	Coefficient of Angular Rigidity, lb × in./in.			
(in.)	(lb/ft)	(Log_{10}w)	t† = 3/8	t = 1/2	t = 3/4	t = 1
1/4	0.16	−0.79	11,900	43,900	167,700	375,000
5/16	0.25	−0.60	9,700	37,700	133,600	300,500
3/8	0.33	−0.44	7,900	31,500	121,000	266,500
1/2	0.65	−0.19	7,100	25,600	82,700	242,700
5/8	1.01	0.01	6,600	20,500	77,200	228,200

*The weight of electrode consumed per unit weld length, w, was computed using the following formula:

$$w = \frac{\frac{1}{2}D_f^2(12)\rho}{DE} = 2.59D_f^2$$

where w = weight of electrode consumed per unit weld length, in.; D_f = fillet weld leg size, in.; ρ = density of steel (0.28 lb/in.^{3}); and DE = deposition efficiency, which is 0.657.

†t = Plate thickness, in.

Table 7.7
Coefficient of Angular Rigidity, C, for Low-Carbon Steel
(SI Units)

Fillet Weld Size, D_f	Weight of Electrode Consumed per Unit Weld Length, w*	Logarithm of Electrode Weight	Coefficient of Angular Rigidity, kg × mm/mm			
(mm)	(g/cm)	(Log_{10}w)	t† = 10	t = 13	t = 18	t = 25.4
6.58	2.51	0.4	5400	19 900	76 100	170 100
7.38	3.16	0.5	4700	18 000	65 200	142 400
8.29	3.98	0.6	4100	16 300	56 100	130 200
9.30	5.01	0.7	3800	15 000	48 800	125 000
10.45	6.31	0.8	3500	13 600	43 000	116 800
12.20	7.95	0.9	3300	12 200	38 900	112 000
13.15	10.00	1.0	3100	11 000	36 100	108 200
14.80	12.60	1.1	3000	9 800	35 200	105 000
16.55	15.85	1.2	2950	8 800	34 800	102 000

*The weight of electrode consumed per unit weld length, w, was computed using the following formula:

$$w = \frac{\frac{1}{2}D_f^2\left(x10^{-2}\right)\rho}{DE} = 0.058D_f^2$$

where w = weight of electrode consumed per unit weld length, mm; D_f = fillet weld leg size, mm; ρ = density of the steel (7.85 g/cm^3); and DE = deposition efficiency, which is 0.657.

†t = Plate thickness, mm.

Table 7.8
Coefficient of Angular Rigidity, C, for Aluminum
(U.S. Customary Units)

Fillet Weld Size, D_f	Weight of Electrode Consumed per Unit Weld Length, w*	Logarithm of Electrode Weight	Coefficient of Angular Rigidity, lb × in./in.					
(in.)	(lb/ft)	(Log_{10}w)	$t^†$ = 1/8	t = 1/4	t = 3/8	t = 1/2	t = 5/8	t = 3/4
3/8	0.08	–1.07	121	1,680	30,000	45,900	55,800	159,800
7/16	0.12	–0.94	115	1,600	17,400	37,500	39,700	70,100
1/2	0.15	–0.82	105	1,480	11,000	27,300	24,500	43,200
5/8	0.24	–0.63	88	1,260	7,500	18,400	14,300	28,000

*The weight of electrode consumed per unit weld length, w, was computed using the following formula:

$$w = \frac{\frac{1}{2} D_f^2 (12) \rho}{DE} = 0.605\, D_f^2$$

where w = weight of electrode consumed per unit weld length, in.; D_f = fillet weld leg size, in.; ρ = density of aluminum (0.1 lb/in.^{3}); and DE = deposition efficiency, which is 0.95.

†t = Plate thickness, in.

Table 7.9
Coefficient of Angular Rigidity, C, for Aluminum
(SI Units)

Fillet Weld Size, D_f	Weight of Electrode Consumed per Unit Weld Length, w*	Logarithm of Electrode Weight	Coefficient of Angular Rigidity, kg × mm/mm					
(mm)	(g/cm)	(Log_{10}w)	$t^†$ = 3.18	t = 6.14	t = 9.5	t = 12.7	t = 15.9	t = 19.1
8.969	1.122	0.05	57	782	14 390	22 800	31 000	78 400
9.567	1.259	0.1	55	762	13 600	20 800	25 300	72 500
10.660	1.585	0.2	52	725	7 900	17 000	18 000	31 800
11.960	1.995	0.3	49	686	5 600	13 800	12 900	22 200
13.420	2.512	0.4	46	645	4 300	11 000	9 200	17 000
15.057	3.162	0.5	43	608	3 600	8 900	6 900	13 500

*The weight of electrode consumed per unit weld length, w, was computed using the following formula:

$$w = \frac{\frac{1}{2} D_f^2 \left(x10^{-2}\right) \rho}{DE} = 0.058\, D_f^2$$

where w = weight of electrode consumed per unit weld length, mm; D_f = fillet weld leg size, mm; ρ = density of aluminum (2.65 g/cm^3); and DE = deposition efficiency, which is 0.95.

†t = Plate thickness, mm.

The final step is to determine the angular change of a leg, D_f, of an unrestrained fillet weld. To estimate the angular change, ϕ_0, for steel and aluminum, parameter w, which denotes the weight of electrode deposited per unit length of weld, must be determined from Figure 7.45 and Figure 7.46 for U.S. customary and SI units, respectively. Parameter w is related to the deposition efficiency, *DE*, of the process, the density of the weld metal, ρ, and the fillet weld leg size, D_f.

The value of the angular change, ϕ_0, can be estimated from Figures 7.45 or 7.46, whereas the amount of distortion, δ, can be determined from Equations (7.19) and (7.20).

Comparison of Angular Distortion in Aluminum and Steel Fillet Welds

The above analysis was performed on aluminum and steel designs within the ranges shown in Table 7.10. The calculated values of out-of-plane distortion at the midspan, δ_m, for aluminum and steel fillet weld distortions are shown in Figure 7.47. These results indicate that the amount of angular distortion in fillet welds made in aluminum is significantly lower than that of fillet welds of the same size made in steel.

BENDING DISTORTIONS INDUCED BY LONGITUDINAL SHRINKAGE

When the weld line fails to coincide with the neutral axis of a welded structure, the longitudinal shrinkage of the weld metal induces bending moments, resulting in the longitudinal distortion of the structure. A theory similar to the bending beam theory has been developed for the analysis of longitudinal distortion caused by the welding of a long slender beam,[62] as shown in Figure 7.48.

Longitudinal residual stress, σ_x, and the curvature of longitudinal distortion, $1/R_c$, are presented in the following expressions:

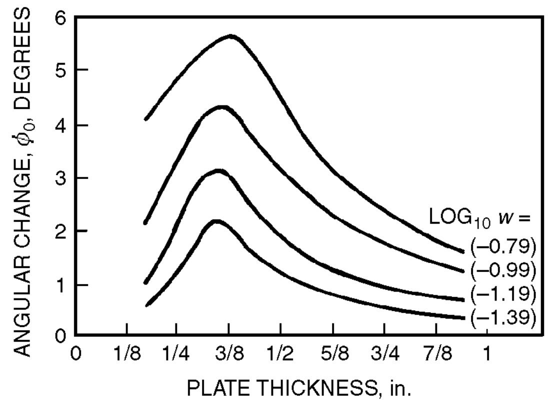
$$\sigma_x = -E\varepsilon_x'' + \frac{M_y^*}{I_y} z + \frac{P_x^*}{A}$$

$$\frac{1}{R_c} = \frac{M_y^*}{EI_y} = \frac{P_x{}^* l^*}{EI_y} \tag{7.26}$$

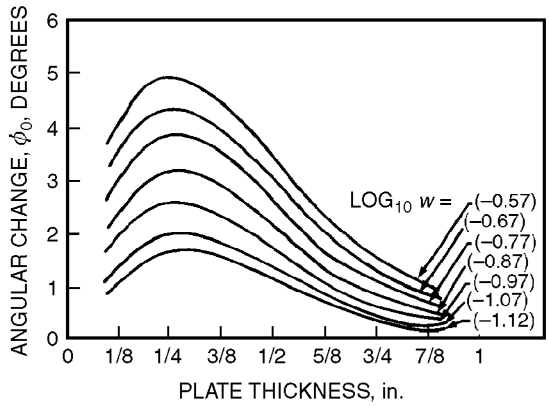
where

σ_x = Longitudinal residual stress, ksi (MPa);
E = Modulus of elasticity, ksi (MPa);
ε_x'' = Incompatible strain;
M_y^* = Apparent shrinkage moment, which equals $\iint E\varepsilon_x'' \, z \, dy \, dz = P_x{}^* l^*$, lb in. (kg mm);
I_y = Moment of inertia of the joint around the neutral axis, in.^{4} (mm^4);
l^* = Distance between the neutral axis and the acting axis of apparent shrinkage force, in. (mm);
P_x^* = Apparent shrinkage force, which equals $\int E\varepsilon_x'' \, dy \, dz$, lb (kg);
x = Longitudinal axis, in. (mm);
A = Cross-sectional area of the joint, in. (mm);
R_c = Radius of curvature of the longitudinal distortion, in. (mm);
y = Longitudinal axis, in. (mm); and
z = Vertical axis, in. (mm).

62. Sasyama, T., K. Masubuchi, and I. Moriguchi, 1955, *Longitudinal Distortion of a Long Beam due to Fillet Welding*, Document X-88-55, London: International Institute of Welding; Masubuchi, K., 1970, *Control of Distortion and Shrinkage in Welding*, Welding Research Council Bulletin 149, New York: Welding Research Council.



LIVE GRAPH
Click here to view
(A) Steel



LIVE GRAPH
Click here to view
(B) Aluminum

Figure 7.45—Effect of Plate Thickness, *t*, and Filler Metal Weight, *w*, per Unit Length of Weld on Angular Change in Unrestrained Fillet Welds, ϕ_o: (A) Steel and (B) Aluminum (U.S. Customary Units)

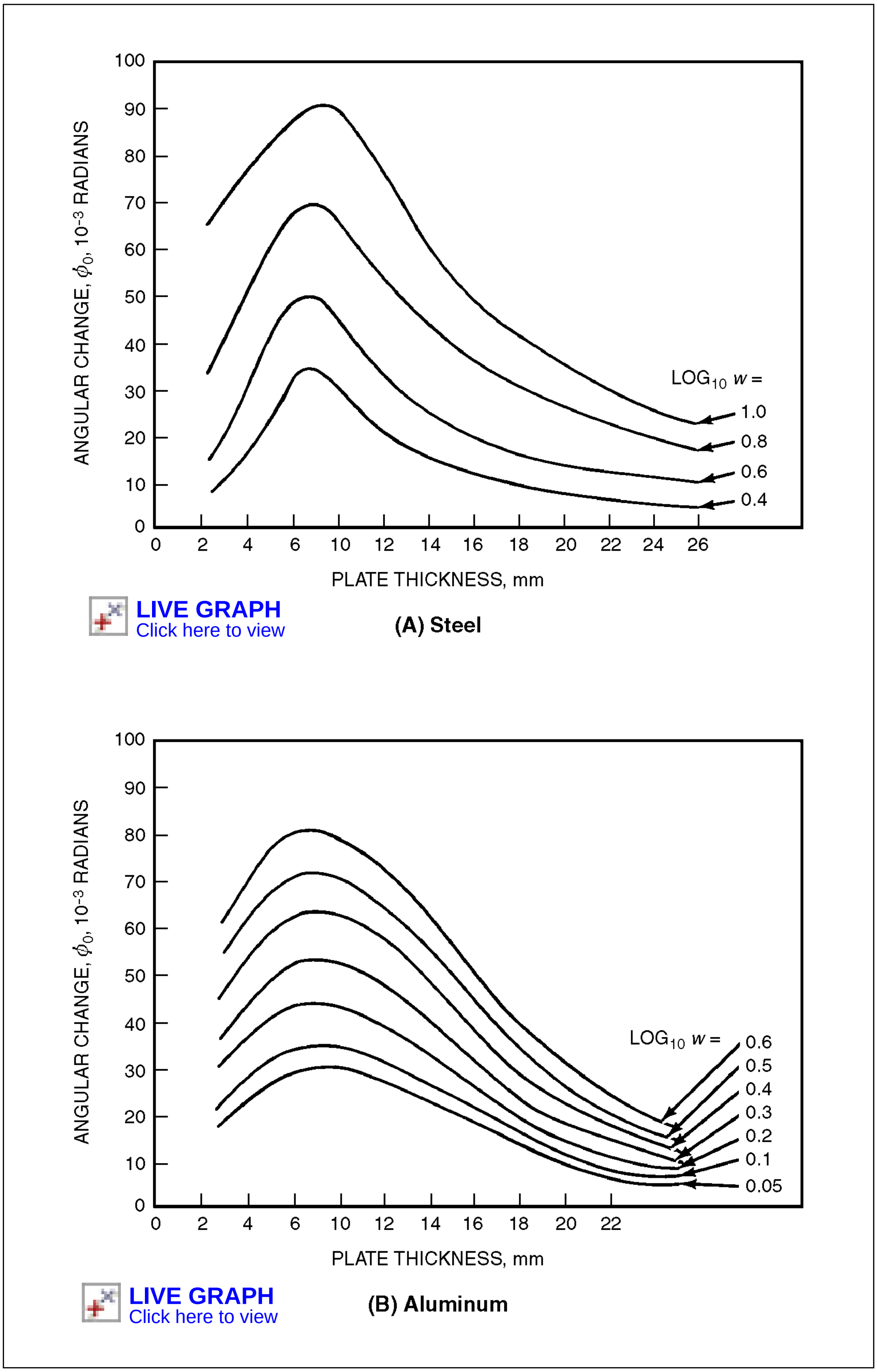


Figure 7.46—Effect of Plate Thickness, *t*, and Filler Metal Weight, *t*, per Unit Length of Weld on the Angular Change in Unrestrained Fillet Welds, ϕ_0: (A) Steel and (B) Aluminum (SI Units)

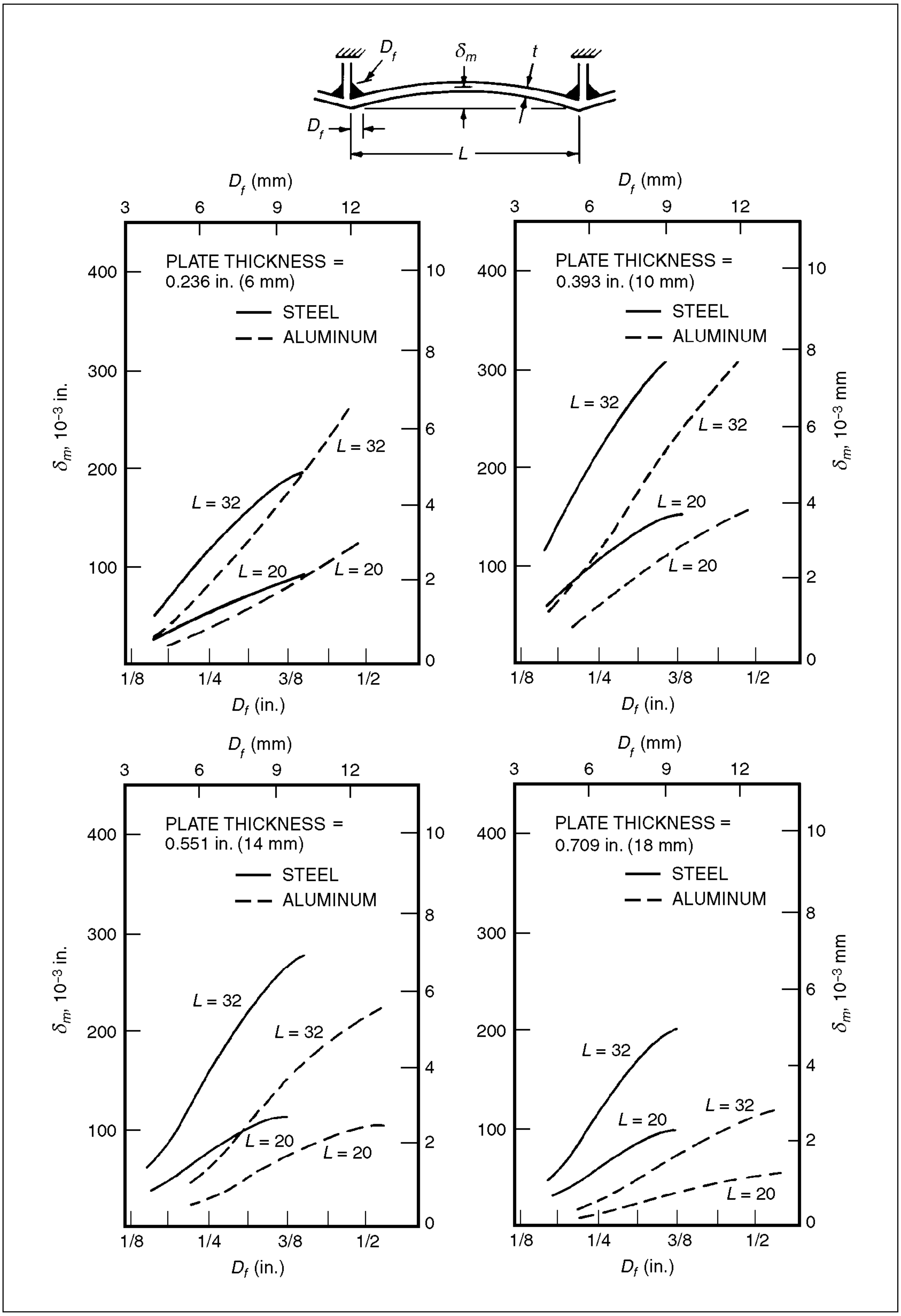
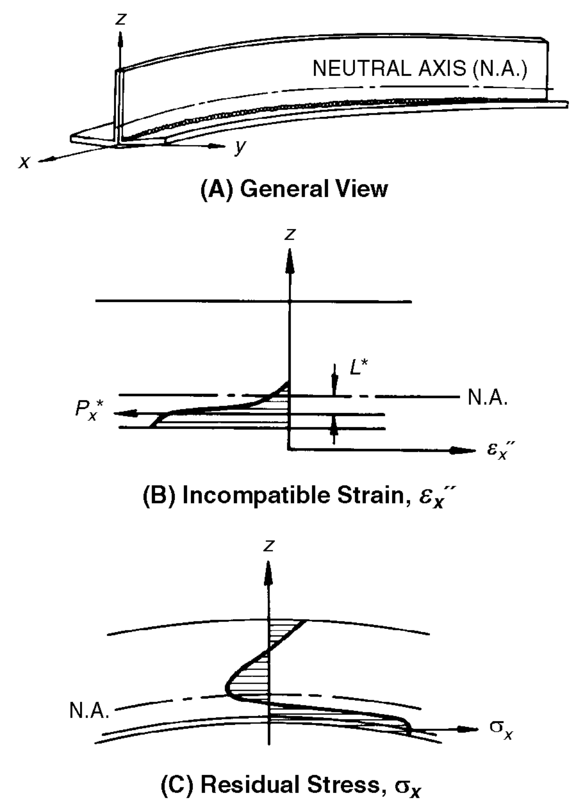


Figure 7.47—Out-of-Plane Distortion, δ_m, as a Function of Plate Thickness, t, Span Length, L, and the Fillet Weld Leg Size, D_f, for Steel and Aluminum

Table 7.10
Ranges of Designs for Calculated Angular Distortion in Steel and Aluminum Fillet Welds

	Inches		Millimeters	
	Min	Max	Min	Max
Plate thickness (t)	0.24	0.70	6	18
Distance between stiffeners (L)	20	32	500	800
Weld leg size (D_f)	3/16	1/2	5	12



Key:
- x = Longitudinal axis, in. (mm)
- z = Vertical axis, in. (mm)
- y = Longitudinal axis, in. (mm)
- P_x^* = Apparent shrinkage force, lb (kg)
- ε_x'' = Incompatible strain
- L^* = Distance between the neutral axis and the acting axis of apparent shrinkage force, in. (mm)

Source: Adapted from Masubuchi, K., 1970, *Control of Distortion and Shrinkage in Welding*, Welding Research Council Bulletin 149, New York: Welding Research Council, Figure 33.

Figure 7.48—Analysis of Longitudinal Distortion in a Fillet Joint: (A) General View; (B) Incompatible Strain, ε_x''; and (C) Longitudinal Residual Stress, σ_x

Equation (7.24) demonstrates that it is necessary to know the distribution of the incompatible strain, ε_x'', in order to determine the distribution of the longitudinal residual stress, σ_x. However, information about the apparent shrinkage moment, M_y^*, is sufficient for determining the amount of distortion, $1/R_c$. The apparent shrinkage moment, M_y^*, is determined when the magnitude of the apparent shrinkage force, P_x^*, and the location of its acting axis are known.

Through experimentation, it has been found that the acting axis of the apparent shrinkage force, P_x^*, is located somewhere in the weld metal. Variable P_x^* is the origin of residual stress, and distortion is produced as the result of the existence of P_x^*.[63]

More information can be obtained when the value of P_x^* rather than the value of distortion itself is used in the analysis of experimental results. For example, in discussing the influence of various factors on the magnitude of distortion, it is possible to classify the factors into those attributable to the change in geometry (A, I_y, or l^*) and those attributed to the change in the value of P_x^* itself.

The increase of longitudinal distortion (apparent shrinkage force, P_x^*) during multipass welding is shown in Figure 7.49. The specimens investigated were mild steel plates 48 in. (1200 mm) in length by 1/2 in. (13 mm) thick. After the first layer, the values of P_x^* increased proportionally with the weight per weld length of electrode consumed. More distortion occurred in the first layer than in subsequent layers. Intermittent fillet welding was used on Specimen I-4, whereas continuous fillet welding was performed on the other specimens. The results are shown in Figure 7.49. Practically no distortion was produced in the specimen welded with the intermittent fillet, probably because longitudinal residual stress does not reach a high value in a short intermittent weld.[64]

63. See Reference 62.
64. The reduction in angular change by the use of intermittent welding may not be as great as that obtained with respect to longitudinal distortion, per Masubuchi, K., 1980, *Analysis of Welded Structures—Residual Stresses, Distortion, and Their Consequences*, New York: Pergamon Press.

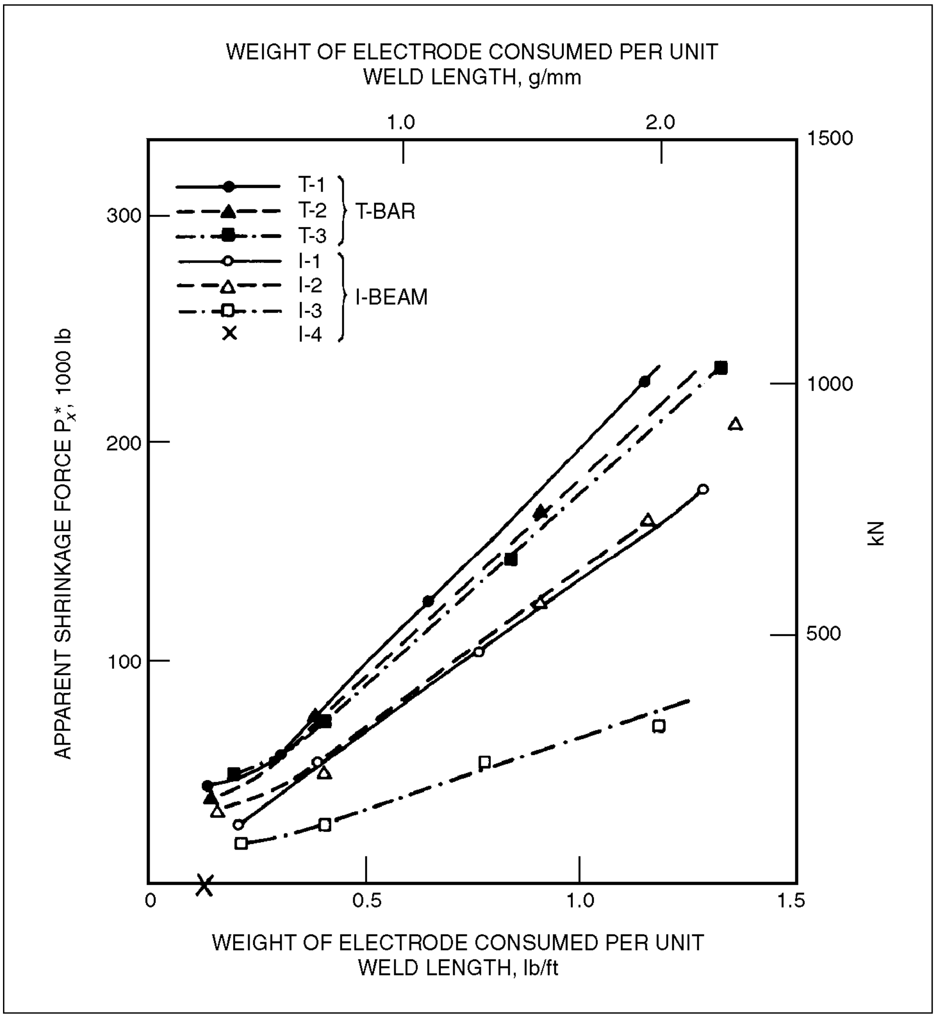


Figure 7.49—Effect of Filler Metal Consumed on the Apparent Shrinkage Force, P_x^*

Figure 7.50 compares values of longitudinal bending distortion expressed in terms of the radius of curvature of built-up beams in steel and aluminum.[65] The aluminum weldments distorted less than the steel weldments, perhaps because the temperature distribution in the *z*-direction is more uniform in an aluminum weldment than in a steel weldment.

BUCKLING DISTORTION

When thin plates are welded, residual compressive stresses are produced in areas away from the weld and cause buckling. Buckling distortion occurs when the length of the specimen exceeds a critical length for a given thickness welded under certain conditions or the welding heat input exceeds certain amounts critical for the specimen geometry.

In studying weld distortions in thin-plate structures, it is important to determine whether the distortion is produced by buckling or by bending. Buckling distortion differs from other types of distortion, such as that produced by bending, in two ways: (1) in buckling, there may be more than one stable deformed shape and (2) the amount of deformation due to buckling is much greater.

The most effective methods of controlling buckling distortion is to prevent its occurrence by (1) selecting the proper geometry for the weldment (plates that are sufficiently thick and a free span length that is sufficiently small) or (2) limiting the input of the welding heat, or (3) both.

65. Yamamoto, G., 1975, Study of Longitudinal Distortion of Welded Beams, M.S. thesis, Massachusetts Institute of Technology.

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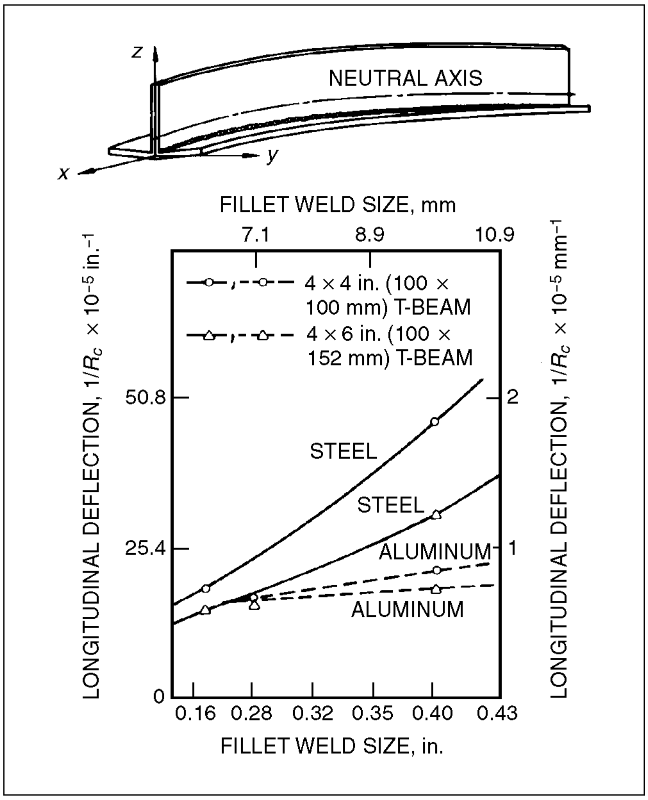

Figure 7.50—Effect of Fillet Weld Size on Longitudinal Deflection in T-Section Beams in Terms of Radius of Curvature, R_c

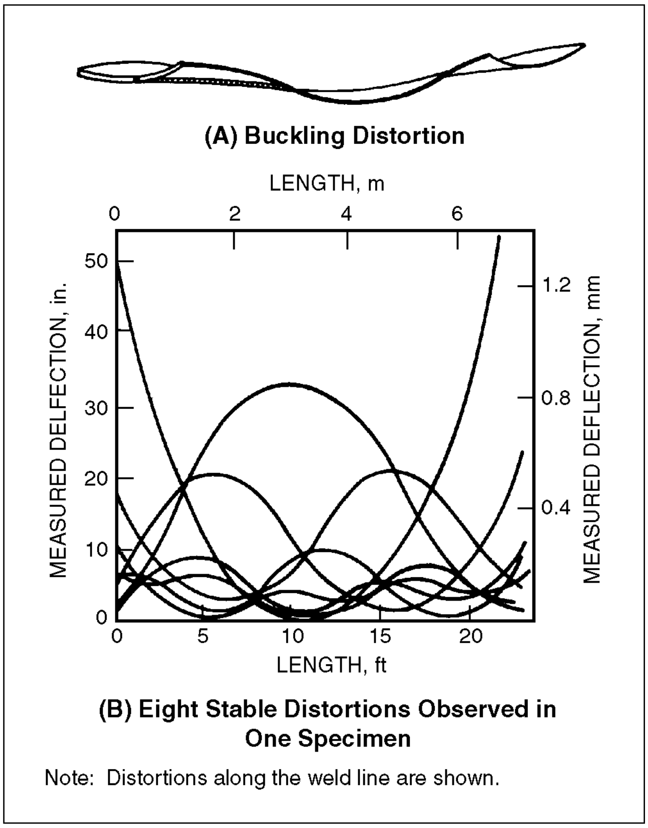

Figure 7.51—Buckling Distortion of a Bead-on-Plate Weld

Buckling distortion of welded plates resulting from residual stresses has been the subject of several studies.[66] One of these[67] addressed the buckling distortion of steel strips 0.09 in. (2.3 mm) thick by 280 in. (7 m) in length. The width of the strips varied from 4 in. to 16 in. (100 mm to 400 mm). The strips were welded along the centerline using submerged arc welding, and the buckling distortions were observed. One specimen exhibited eight different stable deformation patterns along the centerline of the weld. These patterns are depicted in Figure 7.51.

To investigate buckling in stiffened thin-wall structures, experiments have been carried out on thin plates with stiffeners that have been joined to the plate edges with fillet welds.[68] The central deflection (out-of-plane distortion) of low-carbon steel panels was measured for several values of plate thickness, panel dimensions, and heat input using both shielded metal arc and gas tungsten arc welding. The test conditions are summarized in Table 7.11.

Figure 7.52 illustrates the manner in which distortion in the thickness direction at the center of the panel (z-direction distortion at $x = y = 0$) changed during welding. Bottom plates were 20 in. by 20 in. by 1/4 in. (500 mm by 500 mm by 6.4 mm) in size. Stiffeners were

66. Masubuchi, K., 1954, Buckling-Type Deformation of Thin Plate due to Welding, in *Proceedings for the Third International Congress for Applied Mechanics of Japan*. Tokyo: Committee on Theoretical and Applied Mechanics of the Science Council of Japan; Watanabe, M., and K. Satoh, 1961, Effect of Welding Conditions on the Shrinkage Distortion in Welded Structures, *Welding Journal* 40(8): 377-s–384-s; Terai, K., S. Matsui, and T. Kinoshita, 1978, Study on Prevention of Welding Deformation in Thin Plate Structures, *Kawasaki Technical Review* 61(August): 61–66; Tsai, C. L., S. C. Park, and W. T. Cheng, 1999, Welding Distortion of a Thin-Plate Panel Structure, *Welding Journal* 78(5): 156-s–165-s; Michaleris, P., J. Dantzig, and D. Tortorelli, 1999, Minimization of Welding Residual Stress and Distortion in Large Structures, *Welding Journal* 78(11): 361-s–372-s.

67. Masubuchi, K., 1954, Buckling-Type Deformation of Thin Plate due to Welding, in *Proceedings for the Third International Congress for Applied Mechanics of Japan*, Tokyo: Committee on Theoretical and Applied Mechanics of the Science Council of Japan.

68. Terai, K., S. Matsui, and T. Kinoshita, 1978, Study on Prevention of Welding Deformation in Thin Plate Structures, *Kawasaki Technical Review* 61(August): 61–66.

Table 7.11
Summary of Conditions for Buckling Tests*

	U.S. Customary Units		SI Units	
	Min	Max	Min	Max
Plate thickness	0.18 in.	0.40 in.	4.5 mm	10 mm
Panel dimensions	20 in. × 20 in.	40 in. × 40 in.	500 mm × 500 mm	1000 mm × 1000 mm
Heat input	19,200 J/in.	34,300 J/in.	7560 J/cm	13 500 J/cm

*Experiments were conducted using the shielded metal arc and the gas tungsten arc processes.

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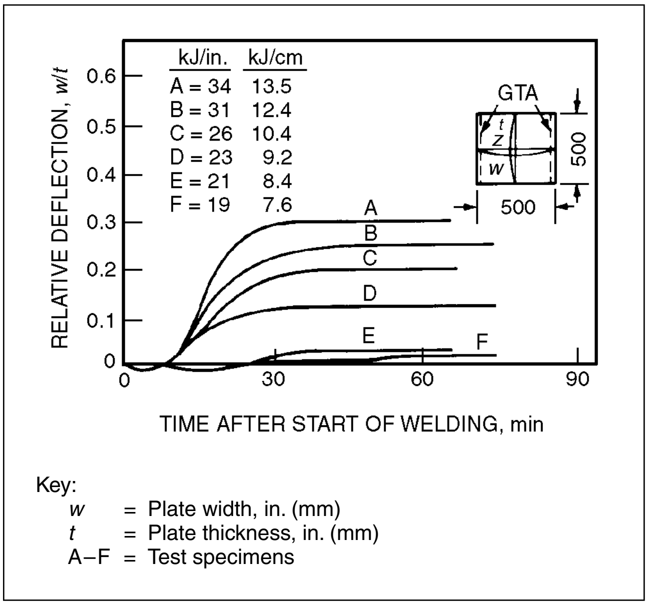

Figure 7.52—Effect of Time after Start of Welding on the Ratio of Central Deflection to Plate Thickness (Relative Deflection, *w/t*)

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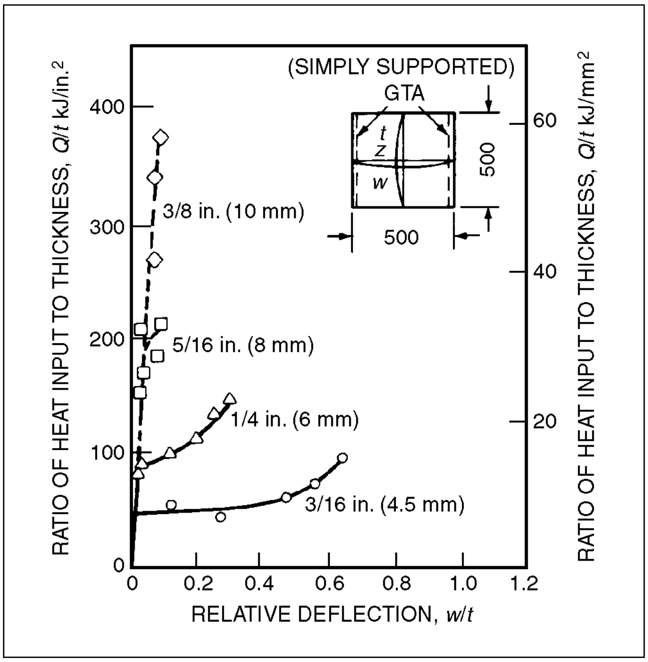

Figure 7.53—Effect of Relative Deflection (*w/t*) on the Ratio of Heat Input to Thickness

fillet welded to plates using gas tungsten arc welding. Shown in the ordinate is the ratio of deflection, *w/t*, which is referred to as relative distortion here.

The final condition of the panel was reached approximately 30 minutes after the start of welding. This amount of time was apparently required for the panel to reach thermal equilibrium. The out-of-plane distortion increased significantly when the heat input increased from 21,000 J/in. (8400 J/cm) to 23,000 J/in. (9240 J/cm). Results similar to those shown in Figure 7.50 were obtained when experiments were performed on specimens with different panel sizes, plate thickness values, and welding heat input conditions.

Figure 7.53 presents the experimental results obtained on panels 20 in. by 20 in. (500 mm by 500 mm) in size and different thicknesses ranging from 3/16 in. (4.5 mm) to 3/8 in. (10 mm). Shown are the relationships between (1) the relative deflection, *w/t,* measured at the panel center after the specimens cooled and (2) the ratio between the welding heat input, *Q* (kJ/in. [kJ/cm]), and the plate thickness, *t*.

The results clearly indicate that the amount of relative deflection, *w/t* increased dramatically when the ratio of welding heat input and the plate thickness exceeded certain amounts, indicating that buckling occurred when the heat input surpassed a certain

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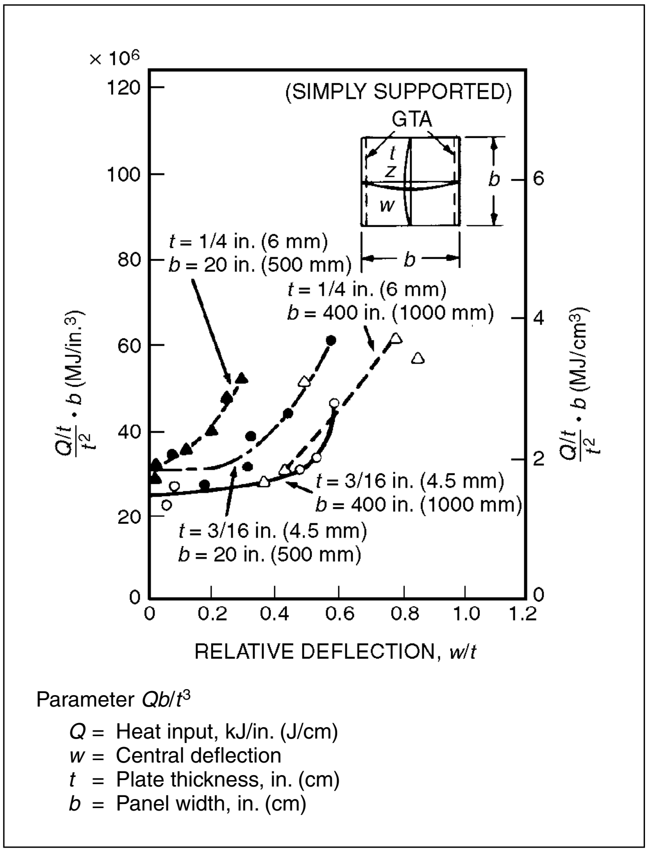

Source: Terai, K., S. Matsui, and T. Kinoshita, 1978, Study on Prevention of Welding Deformation in Thin Plate Structures, *Kawasaki Technical Review* 61 (August): 61–66.

Figure 7.54—Effect of Relative Deflection (w/t) on Parameter Qb/t^3

critical amount. Also, the critical value of Q/t, which causes buckling, increased as the plate thickness increased.

Figure 7.54 summarizes the experimental results obtained from studies of several panels with different widths, b, and plate thicknesses, t, which were welded under different levels of welding heat input, Q.

From Figure 7.54, it is concluded that buckling distortion occurred when the critical heat input, H_{cr}, for a panel was defined as follows:

$$H_{cr} > 33 \text{ MJ/in.}^3 \ (2 \text{ MJ/cm}^3) \tag{7.27}$$

where

H_{cr} = Critical heat input, which equals $\dfrac{Q}{t^3}b$
Q = Heat input, kJ/in. (J/cm);
t = Thickness, in. (cm); and
b = Panel width, in. (cm).

COMPARISON OF DISTORTION IN ALUMINUM AND STEEL WELDMENTS

Although most information on weld distortion pertains to steel weldments, some information on distortion in aluminum weldments is available.[69]

Compared with steel, aluminum has the following physical characteristics:

1. The value of thermal conductivity of aluminum is about five times that of steel;
2. The coefficient of linear thermal expansion of aluminum is about two times that of steel; and
3. The modulus of elasticity of aluminum is about one third that of steel.

Transverse Shrinkage in Butt Joints

The transverse shrinkage that occurs in butt joints made in aluminum is considerably greater than that of steel joints of similar dimensions. This is the case because the welding heat is conducted into wider regions in aluminum welds than in steel welds. Inasmuch as most of the transverse shrinkage results from the shrinkage of the base metal, considerably more transverse shrinkage is produced in aluminum welds than in steel welds.

Angular Change in Fillet Welds

As shown in Figure 7.50, fewer angular changes occur in aluminum fillet welds than in steel fillet welds. Angular change is caused by temperature differences between the top and the bottom surfaces of the flange plate to which the web is welded. The temperature distribution in the thickness direction is more uniform in aluminum welds than in steel welds because of the aluminum's higher thermal conductivity. Therefore, angular change is less common in aluminum fillet welds than it is in steel fillet welds.

Longitudinal Distortion

Longitudinal distortion, expressed in terms of the radius of curvature of built-up beams in steel and aluminum, is shown in Figure 7.50. It can be observed that the aluminum beams experience less distortion.

69. Masubuchi, K., 1972, *Residual Stresses and Distortion in Welded Aluminum Structures and Their Effects on Service Performance*, Welding Research Council Bulletin 174 (July), New York: Welding Research Council; Masubuchi, K., and V. J. Papazoglou, 1978, Analysis and Control of Distortion in Welded Aluminum Structures, *Transactions of the Society of Naval Architects and Marine Engineers* 86: 77–100.

REDUCING OR CONTROLLING RESIDUAL STRESS AND DISTORTION

To develop effective means for reducing residual stress and distortion, it is essential to understand the manner in which residual stress and distortion are induced and how they are affected by design and welding procedures. The previous discussions should be helpful in determining appropriate weld designs and procedures. Several practical approaches to the reduction of residual stress and the control of distortion are presented below.

REDUCTION OF RESIDUAL STRESS

The effects of residual stress on the service behavior of welded structures vary significantly, depending upon a number of conditions. It is preferable to keep residual stress to a minimum. It is therefore advisable to take precautions to reduce residual stress. This is particularly important when welding thick sections.

Since residual stress and distortion are caused by thermal strains due to welding, a reduction in the volume of weld metal usually results in reduced residual stress and distortion. For example, the use of a U-groove instead of a V-groove should reduce the amount of weld metal. It is desirable to use the smallest groove angles and root openings that provide for adequate accessibility for welding and the production of sound weldments.

In the welding of pipes several techniques are frequently used. These are heat sink welding,[70] induction heating,[71] and backlay welding.[72]

THERMAL METHODS USED TO CONTROL RESIDUAL STRESS

Thermal treatments are often necessary to maintain or restore the properties of the base metal affected by the heat of welding. Thermal treatment may also affect the properties of the weld metal. The extent of the changes in the properties of the base metal, weld metal, and heat-affected zone is determined by the soaking temperature, time, and cooling rate, as well as the material's thickness, grade, and initial temper.

Preheating

The most common thermal treatment applied to weldments is preheating. As discussed previously, the proper use of preheat can minimize the distortion that would normally occur during welding. Distortion and the residual stress are reduced as a result of lower thermal gradients around the weld. In steels, preheat has the beneficial effect of reducing the cracking tendency observed in the heat-affected zone and the weld metal.

Postweld Thermal Treatment

A properly executed postweld heat treatment results in uniform mechanical properties and reduced residual stress. The effects of time at temperature and the stress-relieving temperature on residual stress are shown in Figures 7.55 and 7.56, respectively. When thick weldments require a postweld machining operation, a stress-relief heat treatment is usually necessary to achieve normal machining tolerances.

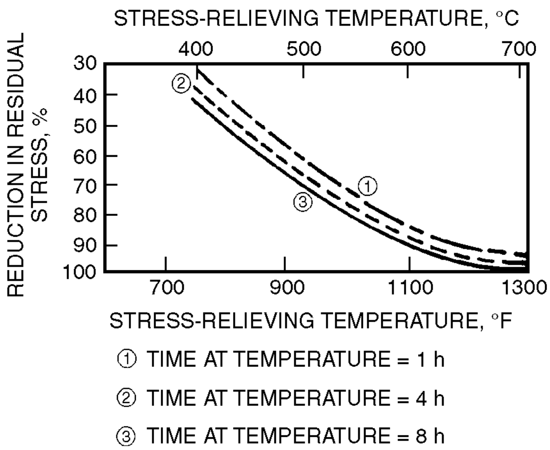

Figure 7.55—Effect of Time at Temperature on the Reduction of Residual Stress

70. Masaoka, L., R. Sasaki, K. Imai, S. Kirihari, M. Miki, T. Koyama, H. Itow, and T. Maruyama, 1978, Mitigation on Inside Surface Residual Stresses of Type 304 Stainless Steel Pipe Running Water Cooling Method, in *Vortrage der 3rd International Kalloquim, Schweissen in der Kerntecknik, Hamburg, Germany*, November 29.
71. Rybicki, E. F., and P. A. McGuire, 1981, A Computational Model for Improving Weld Residual Stresses in Small Diameter Pipes by Induction Heating, *Journal of Pressure Vessel Technology* 103 (August): 294–299.
72. Brust, F. W., and E. F. Rybicki, 1981, A Computational Model of Backlay Welding for Controlling Residual Stresses in Welded Pipes, *Journal of Pressure Vessel Technology* 103 (August): 226–232.

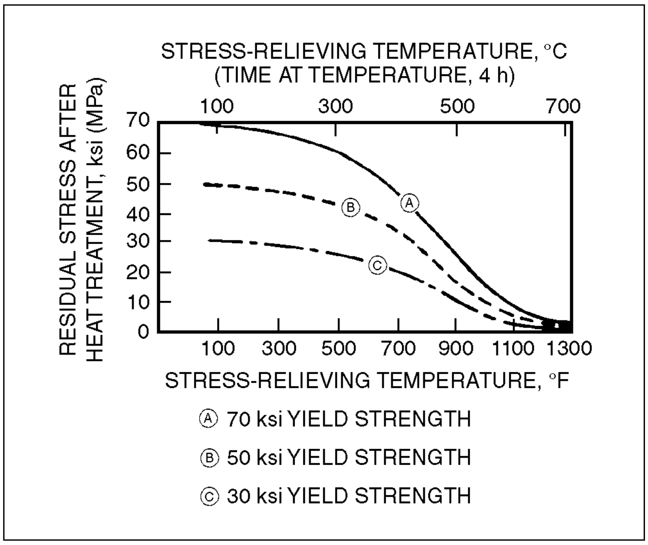

Figure 7.56—Effect of Stress-Relieving Temperature on Residual Stress

CONTROL OF DISTORTION

While distortion due to welding cannot be avoided totally, steps can be taken to minimize the magnitude and effects of distortion. Control of distortion includes consideration during the design stage and the selection of the welding and assembly procedures, as well as the use of techniques such as elastic prestraining and preheating.

Design

The most economical design for a welded fabrication is that which requires the fewest number of parts and a minimum of welding. Economical designs assist in reducing distortion. The type of joint preparation is important, particularly for unrestrained butt joints, because it can influence the amount of angular distortion of the joint.

With respect to fillet welds, the smallest weld that meets the shear strength requirements can be expected to produce the lowest residual stress and distortion. Thus, the use of small fillet welds will prevent overwelding and excessive distortion.

Smart design and proper joint details alone cannot control distortion, but they serve to reduce the magnitude of the problem.

Assembly Procedure

Distortion in some form or another cannot be avoided. Therefore, appropriate steps must be taken to minimize it. Distortion can best be controlled by using one of the following assembly methods. The first method involves estimating the amount of distortion likely to take place during welding and presetting the members to compensate for distortion. In the second method, the job is assembled so that it is nominally correct before welding, and then some form of restraint is used to minimize distortion.

The first method is attractive because the parts have almost complete freedom to move during welding, resulting in lower residual stress than with the second method. However, the first method is difficult to apply, except on relatively simple fabrications. A good approach is to fabricate subassemblies using the first method. The subassemblies can be welded without restraint. This approach is especially attractive when the weldment is made up of a large number of parts. The welded subassemblies may then be assembled together and welded to complete the job. Often, this final welding has to be carried out under conditions of restraint.

Figure 7.57 illustrates the presetting method applied to fillet welds and welds in butt joints. The amount of preset required varies somewhat according to plate thickness, plate width, and the welding procedure to be used. For this reason, it is advisable to establish the correct preset using welding tests rather than personal judgment.

The restrained assembly method is generally preferred because of its comparative simplicity. The restraint may be applied by clamps, the use of fixtures, or simply by adequate tack welding. While this method minimizes distortion, it can result in high residual stress. High residual stress and the risk of cracking can often be minimized by implementing a suitable welding sequence and, with thick sections, by preheating. Where service requirements demand the removal of residual stress, a stress-relieving heat treatment must be applied after welding.

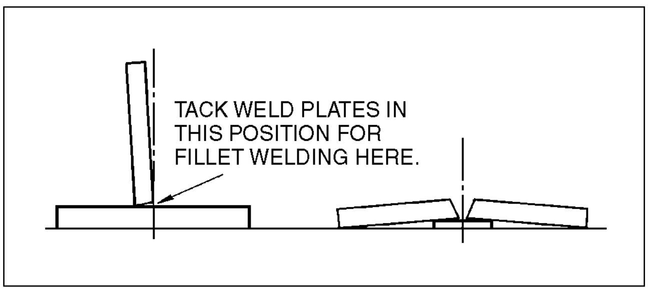

Figure 7.57—Presetting for Fillet Welds and Welds in Butt Joints

An attempt to impose complete restraint may be undesirable, but by restraining movement in one direction and allowing freedom in another, the overall effect can usually be controlled. An example is presented in Figure 7.58, in which the clamping arrangement is designed to prevent angular distortion in a single V-groove weld while permitting transverse shrinkage.

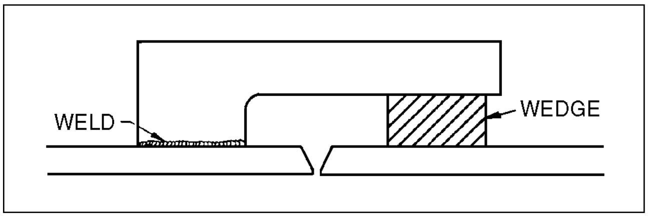

Figure 7.58—Arrangement of a Clamp to Prevent Angular Change while Permitting Transverse Shrinkage

Elastic Prestraining

Elastic prestraining involves bending a plate elastically before stiffeners are fillet welded to it. This technique is shown in Figure 7.59. Angular changes after the removal of the restraint can be reduced significantly using this method.

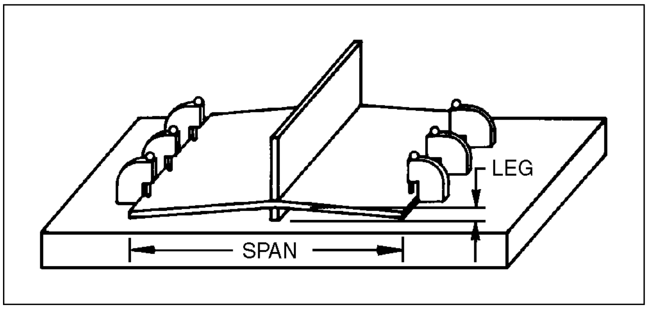

Figure 7.59—Apparatus Used to Weld T-Joints Submitted to Elastic Prestrain by Bolting Down Both Free Ends

Preheating

Preheating may be used as a method of reducing distortion in a weldment. As shown in Figure 7.60, the application of preheat on the top of the flange plate of a T-section increases the angular distortion for some combinations of thickness and welding conditions and decreases it for other combinations. However, preheating the bottom of the flange plate, which helps to balance the heat of welding, reduces angular distortion in all combinations of thickness and welding conditions.

In analyzing experimental results, Watanabe et al. used parameter Z as determined by the following equation:[73]

$$Z = \frac{I}{t\sqrt{vt}} \tag{7.28}$$

where

I = Welding current, A;
t = Thicknesses of horizontal plate, in. (mm); and
v = Welding speed, in./s (cm/s).

Parameter Z indirectly includes the fillet weld size because the weld area is proportional to the ratio of the amperage to the travel speed for consumable electrode welding.

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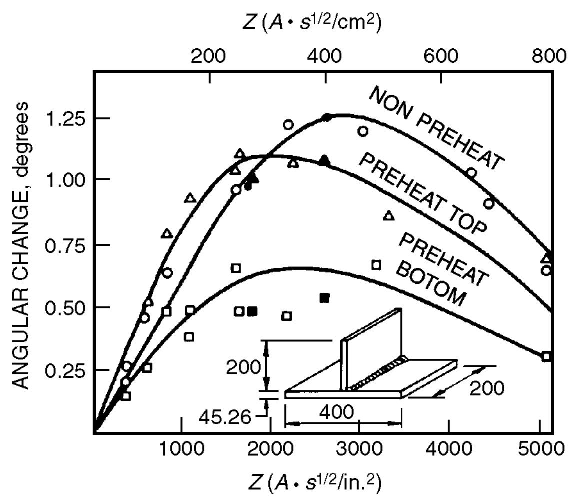

Key:

$Z = \frac{I}{t\sqrt{vt}}$, where I = welding current, amperes; t = thicknesses of the horizontal plate, in. (mm); and v = welding speed, in./s (cm/s).
A = Amperes
s = Seconds

Figure 7.60—Effect of Preheat and Welding Variables on Angular Change in Steel Fillet Welded T-Joints

CORRECTION OF DISTORTION

It is not always possible to control distortion within acceptable limits, especially with a new design or fabrication. In these circumstances, it is usually possible to remove distortion using one or more processes.

73. Watanabe, M., K. Satoh, H Mori, and I. Ichikawa, 1957, Distortion in Web Plate of Welded Built-Up Girders due to Welding Stiffeners and Methods for Decreasing It, *Journal of the Japan Welding Society* 26(12): 591–596 (in Japanese).

Distortion can be removed by producing adequate plastic deformation in the distorted member or section. The required amount of plastic deformation can be obtained using the thermal or mechanical methods discussed below.

Thermal Straightening

Thermal or flame straightening can be used to remove distortion. The distorted area is straightened by heating the appropriate spots from 1100°F to 1200°F (600°C to 650°C) and quenching with air or water. This procedure causes the material to expand locally during heating, and then shrinkage stress tends to straighten the plate or beam. Repeated applications result in additional shrinkage, though each successive application may be less effective. The best procedure is to apply the heat to a pattern of spots or lines in the distorted member.

This technique can also be used to provide desired shape.[74] A bridge girder may require a fixed amount of camber or sweep. Camber can be induced by applying the heat to the outside of one flange along the length of the girder. Sweep can be induced by applying the heat to one edge of each flange along the length of the girder. Initially, the girder bends toward the torches as the flange lengthens due to thermal expansion. When the flange returns to ambient temperature, it will have shortened, and the girder will be bent away from the heated surface. This principle is illustrated in Figure 7.10.

Mechanical Straightening

Distorted members can be straightened mechanically with a press or jacks. In this case, heat may or may not be required for straightening.

CONCLUSION

This chapter describes the causes and distribution of residual stresses that occur in welded joints and weldments. These residual stresses are generated by nonuniform heating and cooling of the weld area due to the heat of the welding process. Methods of calculating and measuring residual stresses in weldments have been described. The effects of residual stresses on the mechanical performance and distortion of weldments have also been covered. The chapter also includes a discussion of methods used to reduce residual stresses in weldments and to control weld distortion.

74. Iwamura, Y., and E. F. Rybicki, 1973, A Transient Elastic-Plastic Thermal Stress Analysis for Flame Forming, *Journal of Engineering for Industry Transactions of the ASME* n.v.(February): 163–171.

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CHAPTER 8

SYMBOLS FOR JOINING AND INSPECTION

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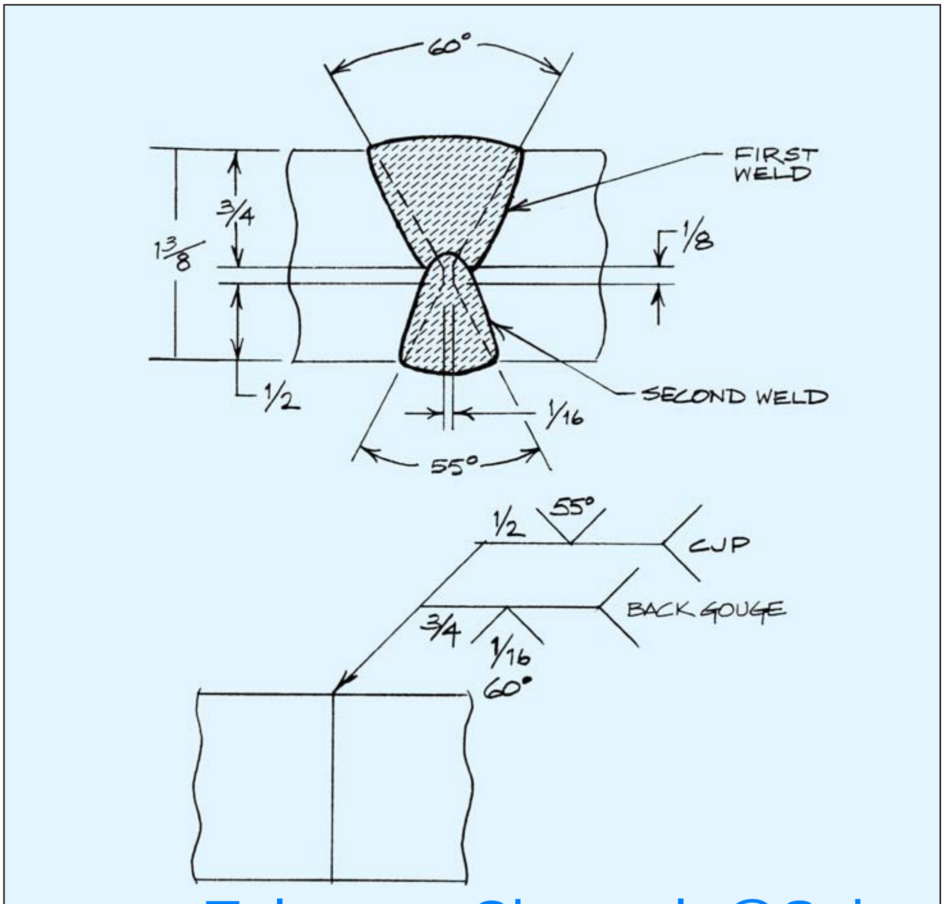


Contents

CHAPTER 8

SYMBOLS FOR JOINING AND INSPECTION

INTRODUCTION

Standard symbols are used universally to indicate precise welding, brazing, and soldering information on engineering drawings. Welding symbols communicate a wealth of information. They specify in a concise manner the design of a weld or welds to be applied to a given joint. In addition, they prescribe the welding process to be used, the size and length of weld, the groove design, the face and root contours, and the sequence of operations, among other information. Symbols are also used to designate the nondestructive examination (NDE) requirements for welded or brazed joints. The examination methods to be implemented are indicated in these symbols.[1] In many cases, not all required information can be conveyed by means of symbols. Thus, supplementary notes or dimensional details, or both, are often included on drawings to provide the fabricator complete requirements.

This chapter discusses the fundamentals and applications of the symbols used in the welding industry. Welding and nondestructive examination symbols trace their origins back to American Welding Society (AWS) committee work done in the 1940s. The latest information on the complete system of joining and nondestructive examination symbols is presented in *Standard Symbols for Welding, Brazing, and Nondestructive Examination,* ANSI/AWS A2.4.[2,3] This publication is the definitive reference for the appropriate symbols and conventions used to convey information regarding welding, brazing, and inspection requirements and should be consulted for updates made since the publication of this chapter.

The reader should note that some of the figures presented to illustrate the concepts discussed in this chapter include dimensions. For purposes of graphical simplicity, these dimensions are presented in U.S. customary units only unless otherwise indicated.

Many of the welding terms included in this chapter are defined in *Standard Welding Terms and Definitions,* AWS A3.0:2001.[4] The reader is advised to become familiar with the terms and definitions applicable to symbols.

1. Nondestructive examination methods, procedures, and the type of discontinuities that each method reveal are discussed in American Welding Society (AWS) Committee on Methods of Inspection, *Guide for the Nondestructive Examination of Welds,* AWS B1.10, Miami: American Welding Society. The selection of examination methods depends upon the quality requirements specified for the production.

2. American Welding Society (AWS) Committee on Definitions and Symbols, *Standard Symbols for Welding, Brazing, and Nondestructive Examination,* ANSI/AWS A2.4, Miami: American Welding Society.

3. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

4. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society.

FUNDAMENTALS

As symbols are used to specify joining and inspection information, this section begins with a description of the desired product, the welded joint. A joint is a junction of the members or the edges of the members that are to be joined or have been joined. The five basic joints used in welding and brazing design are the butt, corner, T-, lap, and edge joints. Schematic illustrations of these joints are presented in Figure 8.1.

Once the desired joints have been designed, welding symbols are typically used on the engineering drawing to specify the required welding information and details. When the details of the weld cannot be adequately communicated by means of welding symbols, additional information is specified in a notation on the drawing.

Symbols may be drawn by any method—electronic, mechanical, or freehand. They must be clear and legible regardless of the method used.

While the use of metric units is growing, U.S. customary units can still be used in welding and examination symbols. However, dual units (i.e., both U.S. customary and SI units) must not be used. If desired, a table of conversions may be included on the drawing. Suggested size dimensions for welding symbol elements are provided in *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4.[5]

With respect to terminology, it is important to note that the terms *weld symbol* and *welding symbol* have different meanings. The weld symbol specifies the type of weld that is prescribed for the application. The weld symbol is part of the welding symbol. Groove weld symbols are similar in shape to the cross section of the desired groove. Other symbols, such as those used for stud and seam welds, are similar in shape to the characteristics of these welds viewed from other orientations. Figure 8.2 presents the weld symbols used for various common welds.

WELDING SYMBOLS

Welding symbols are used to communicate requirements for the desired welding. They typically include the weld symbol and specify the weld location, type, size, and length.

The basic welding symbol is comprised of the reference line, about which the weld symbol and dimensions are located, and an arrow, designating the location for the weld. As shown in Figure 8.3, a tail may be included in the symbol to provide an area to communicate information about the welding specification, the welding process, or other reference data.

5. See Reference 2.

A complete welding symbol consists of the following elements:

1. Reference line (required);
2. Arrow (required);
3. Tail;
4. Basic weld symbol;
5. Dimensions and other data;
6. Finish symbols;
7. Specification, process, or other references; and
8. Supplementary symbols.

The elements of the welding symbol have a standard location with respect to one another. The location of the elements in the welding symbol is illustrated in Figure 8.4.

Apart from the reference line and arrow, which are required, only those elements that provide the required clarity need be specified. The required and optional elements of the welding symbol are described in detail below.

Reference Line

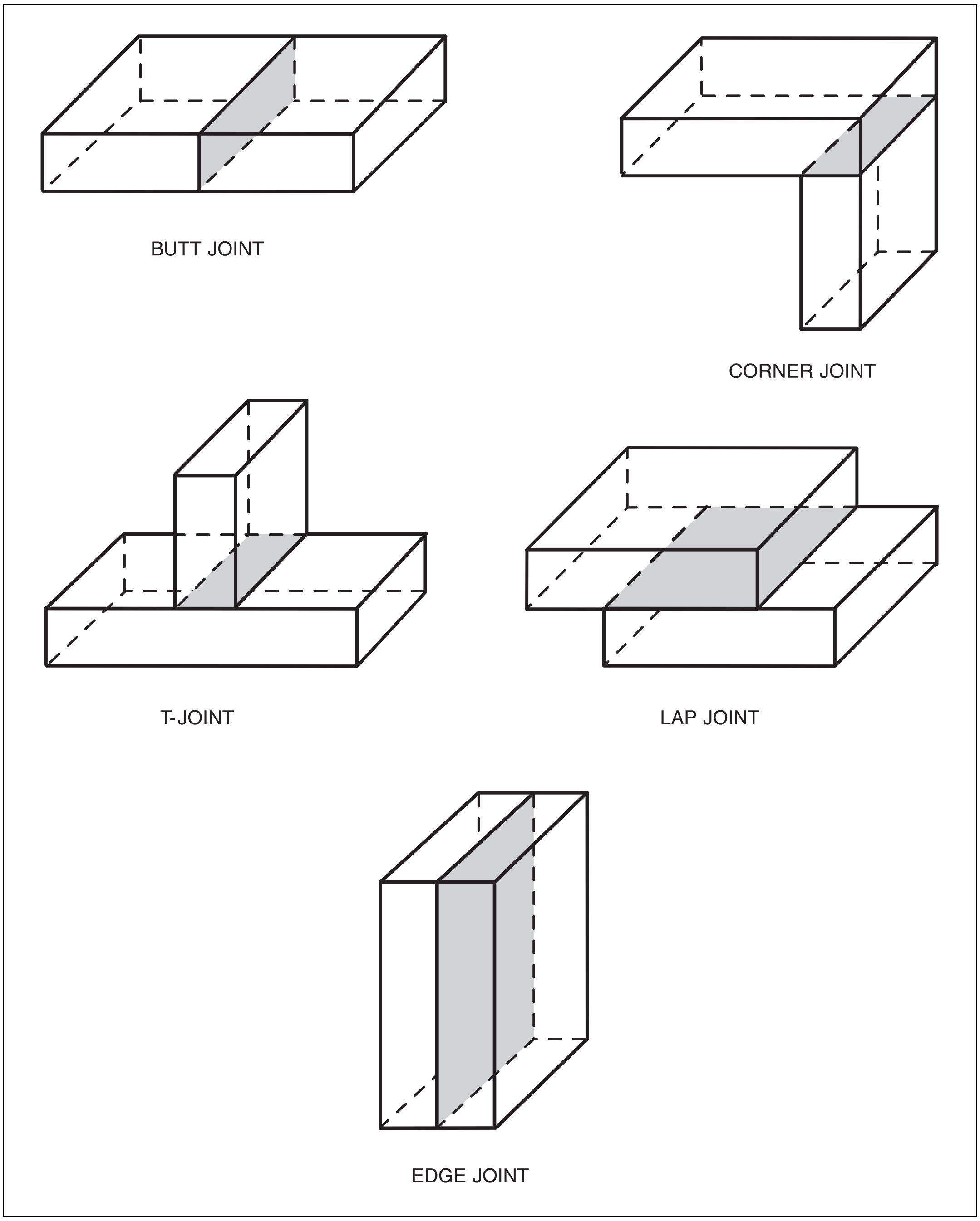
The reference line is the basic and required welding symbol element about which the weld information is located. The reference line is oriented horizontally.

Multiple Reference Lines. As shown in Figure 8.5, two or more reference lines may be used with a single arrow to indicate a sequence of operations. The reference line nearest the tip of the arrow specifies the first operation. The second or more reference lines represent the subsequent operations. Subsequent operations are shown sequentially on other reference lines leading away from the tip of the arrow.

Reference lines are also used to specify data to supplement the welding symbol and to indicate inspection requirements. Figure 8.6 illustrates the application of multiple reference lines to give clear guidance on the procedures (e.g., gouging to sound metal for the weld from the second side).

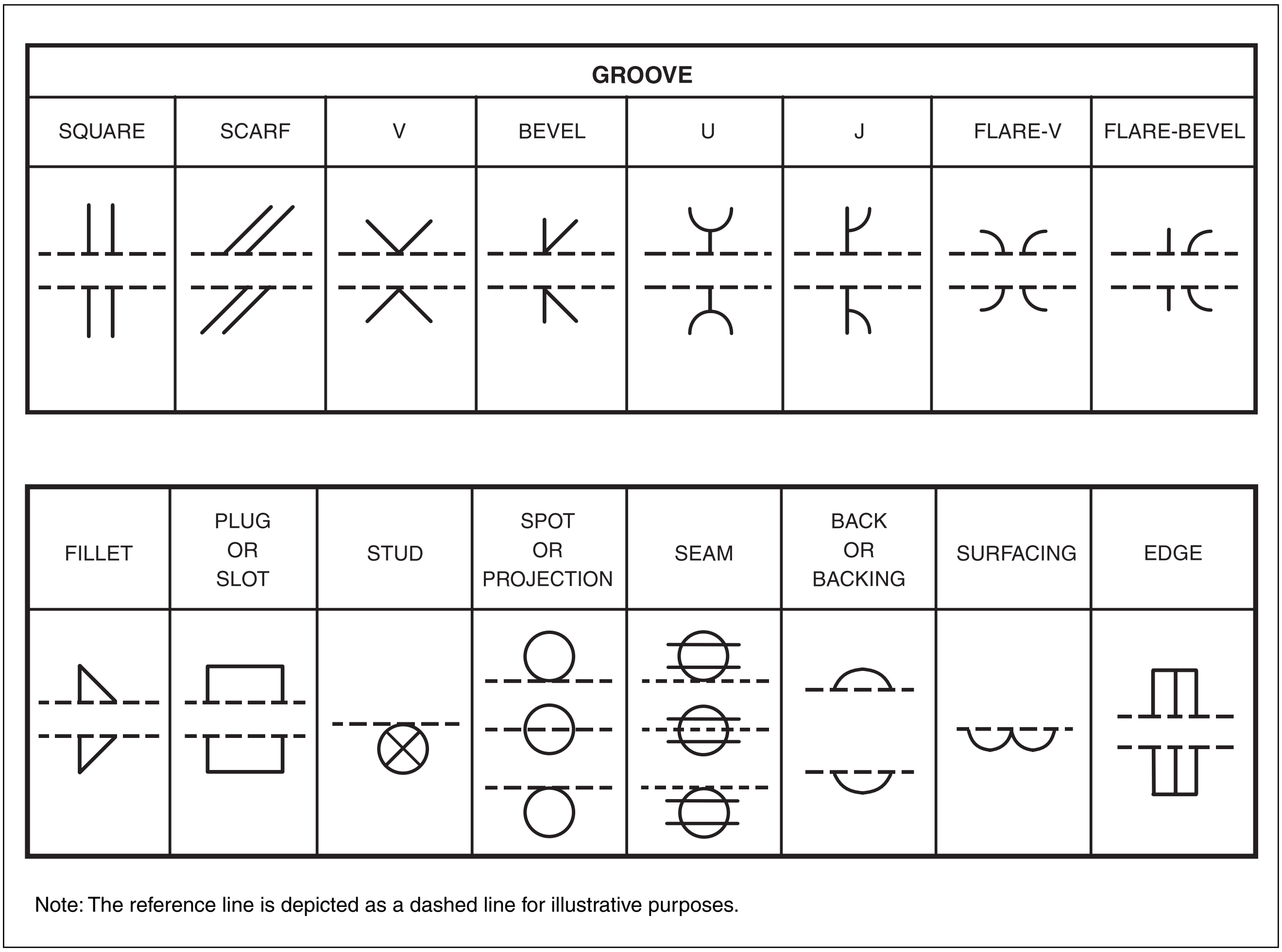
Arrow

The significance of the arrow is illustrated in Figure 8.7. Used in conjunction with the reference line, the arrow establishes the locations of the arrow side and the other side of a joint, as shown in Figure 8.7(A). The arrow clearly points to the location on the drawing that identifies the intended joint to which the welding instructions apply. The arrow side of the reference line is always closest to the reader when the drawing is viewed from the bottom and the reference line is drawn, as preferred, in a horizontal plane. Likewise, the other side of the line provides instructions for the side of the joint furthest from the arrow.



Source: American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 4.

Figure 8.1—Basic Joints



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 1.

Figure 8.2—Weld Symbols

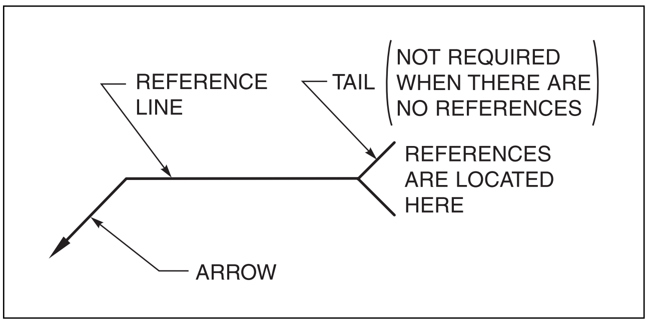
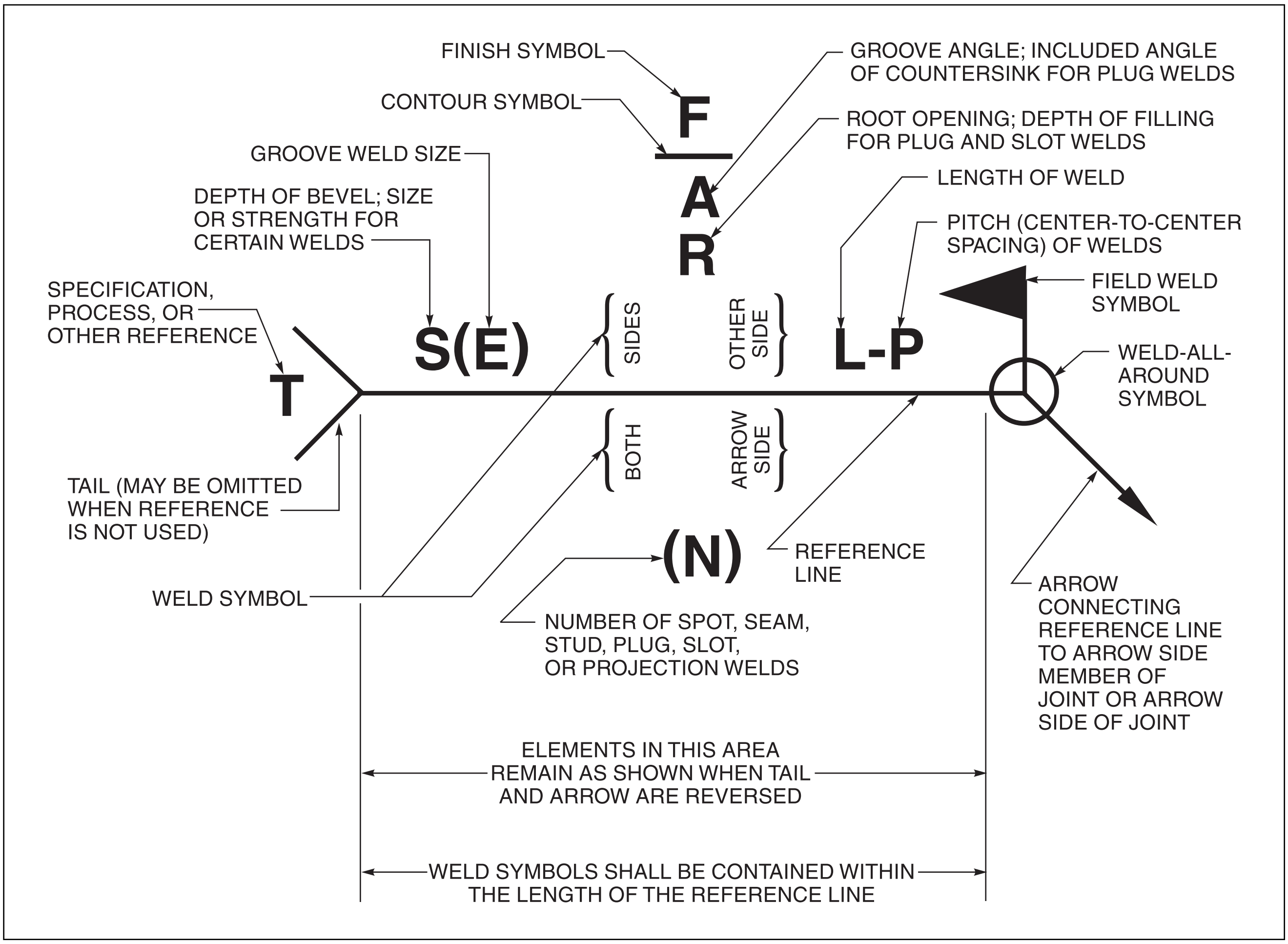


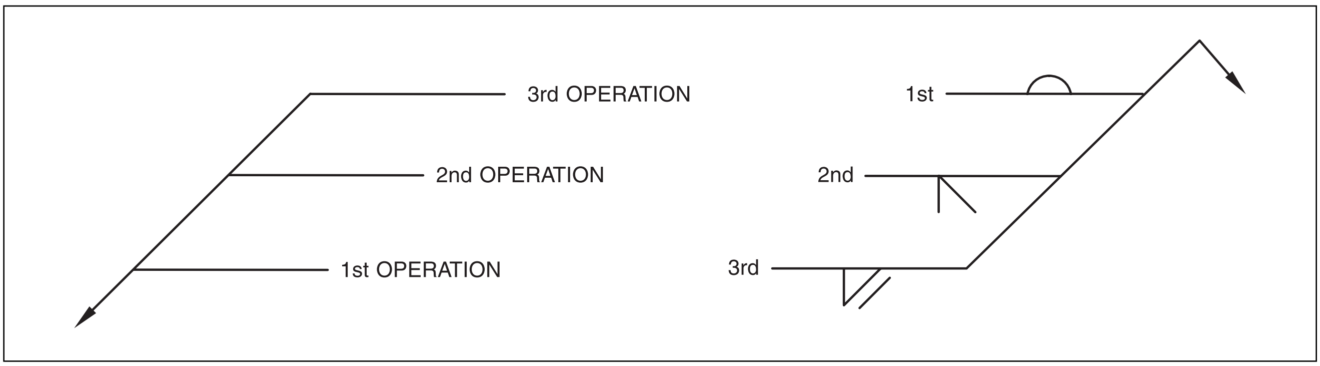
Figure 8.3—Standard Welding Symbol

Figure 8.7(A) offers examples of the use of the terms “arrow side” and “other side” for three common joint geometries. The weld symbol specifying an arrow-side weld is always placed on the lower side of the reference line, as shown in Figure 8.7(B). On the other hand, the weld symbol depicting an other-side weld is placed on the upper side of the reference line, that is, away from the reader when viewed from the bottom, as shown in Figure 8.7(C). Welds on both sides of a joint are prescribed by placing weld symbols on both sides of the reference line, as depicted in Figure 8.7(D).



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 2.

Figure 8.4—Standard Location of the Elements of the Welding Symbol



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, p. 6.

Figure 8.5—Multiple Reference Lines

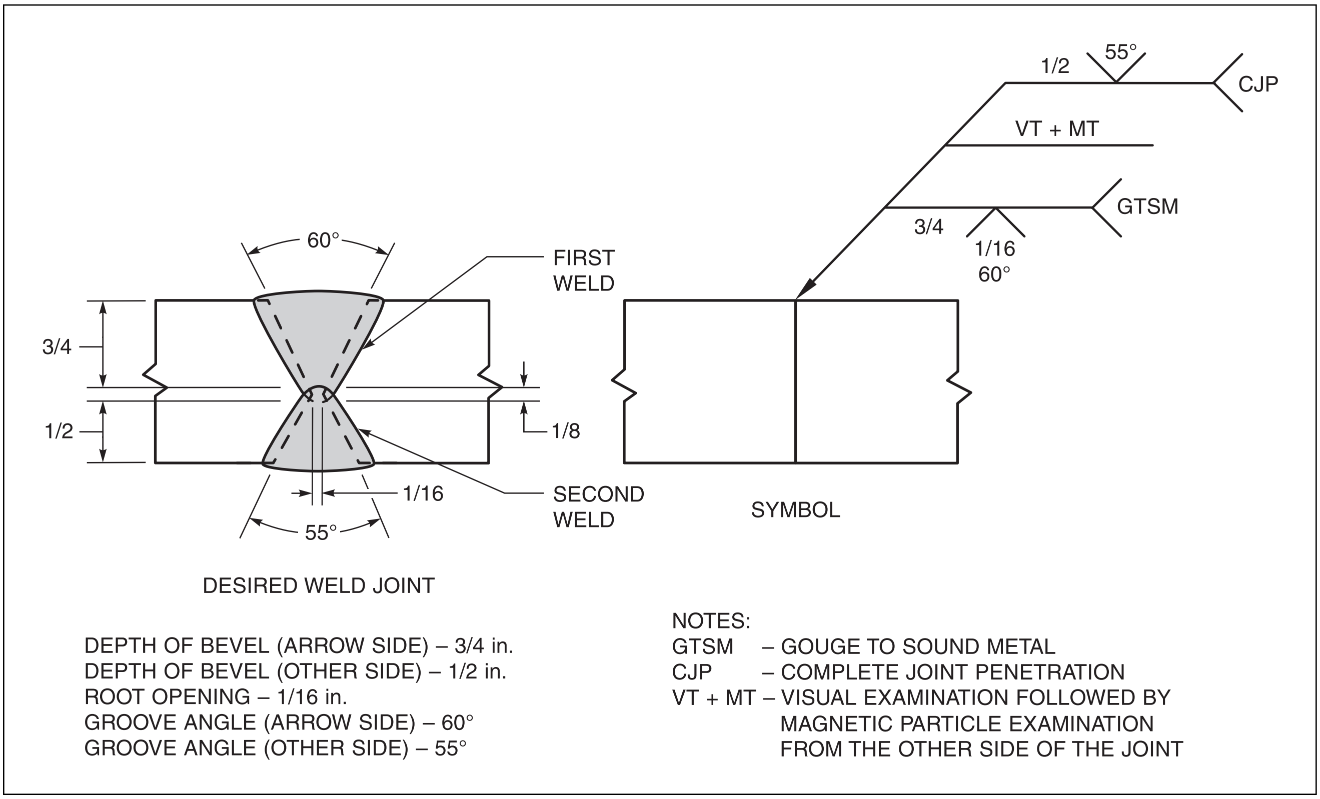


Figure 8.6—Application of Multiple Reference Lines

Some weld symbols have no arrow-side or other-side significance. However, supplementary symbols (see below) used in conjunction with these weld symbols can convey such significance. For example, weld symbols for resistance spot and seam welding have no side significance, as can be observed in Figure 8.7(E). However, gas tungsten arc welding (GTAW), electron beam welding (EBW), or other spot and seam welds may have arrow- and other-side significance.

Tail

When a specification, process, test, or other reference is needed to convey additional requirements of the joint to be manufactured, this information is placed in a tail of the symbol, as shown in Figure 8.7(F). The illustrations on the left and in the center indicate specifications, codes, or other referenced documents. In the illustration on the right, the letter designation "CJP" is used in the tail of the welding symbol to specify that a complete joint penetration groove weld is required, regardless of the joint geometry. As previously explained, the tail may be omitted when no specification, process, or other reference is included in the welding symbol.

Supplementary Data. The tails of any additional reference lines used in the welding symbol convey data that is supplementary to the basic information presented in the welding symbol. Examples of supplementary information include the process, process variation, method of application, and welding procedure number. Figure 8.8 illustrates the communication of supplementary data in additional reference lines.

Basic Weld Symbol

Sixteen basic weld symbols are used. These are shown in Figure 8.2.

Dimensions and Other Data

The dimensions of a weld are shown on the same side of the reference line as the basic weld symbol. The size of the weld is shown to the left of the weld symbol, and the length of the weld is shown on the right. If a length is not given, the weld symbol applies to that portion of the joint between abrupt changes in the direction of welding or between specified dimension lines. If a weld symbol is shown on each side of the reference

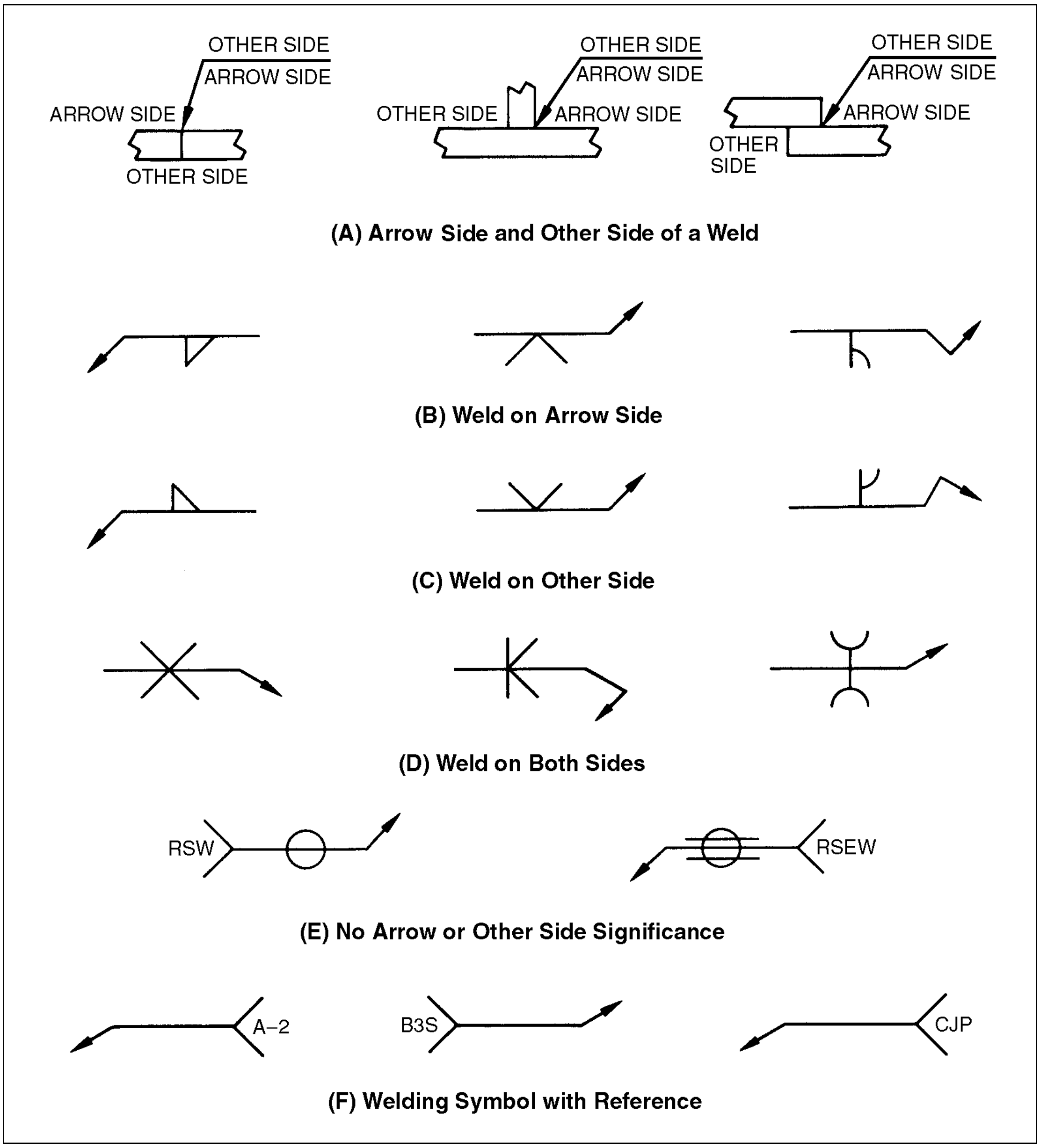
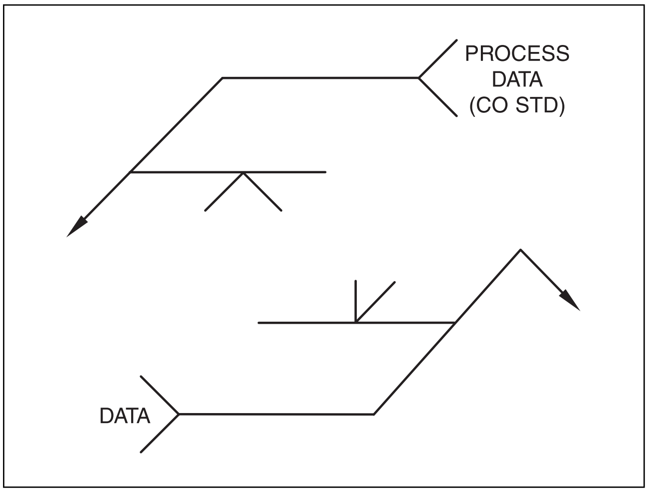


Figure 8.7—Significance of the Arrow in the Welding Symbol

line, the dimensions, if used, must be given for each weld even though both welds are identical.

Either the U.S. customary system of measurement or the International System of Units (SI) may be used when specifying dimensions. However, as noted above, only one system should be used for a project or product.

Examples of symbols indicating the dimensions of typical fillet welds are shown in Figure 8.9. In Figure 8.9(A), a 5/16 in. fillet weld is specified for the arrow side of the T-joint. In Figure 8.9(B), 1/2 in. fillet welds are specified for the arrow side and the other side of the T-joint. In Figure 8.9(C), a 3/8 in. fillet weld and a 1/4 in. fillet weld are specified for the arrow side and the other side of a T-joint, respectively. In Figure 8.9(D), a fillet weld having one 1/4 in. leg and one 1/2 in. leg is specified for the arrow side of the T-joint. The dimensions "1/4 × 1/2" noted adjacent to the fillet weld symbol do not specify leg orientation, so the drawing and a reference in the tail are used to clarify the requirements. In Figure 8.9(E), a continuous fillet weld is required on



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination,* ANSI/AWS A2.4-98, Miami: American Welding Society, p. 6.

Figure 8.8—Communication of Supplementary Data in Additional Reference Lines

the arrow side of the joint since no weld length is specified numerically to the right of the fillet weld symbol. The size of the fillet weld is not specified. In Figure 8.9(F), a fillet weld 12 in. in length is specified on the arrow side of the joint. The specific location of the 12 in. long weld is shown by the notation "3 in." on the drawing. The size of the fillet weld is not specified.

If a weld in a joint is to be intermittent, the length of the segments and the pitch (i.e., the center-to-center spacing) are placed to the right of the weld symbol, as can be observed in Figure 8.10.

Finishing Symbols

Finishing symbols can be used to specify a mechanical method of achieving the required weld control. They are used in conjunction with contour symbols (see "Supplementary Symbols"). Figure 8.11 presents the finishing symbols and their meaning.

Specification, Process, and Other References

Welding symbols also offer a means of conveying other more detailed welding requirements or instructions. Most often, this information is included in the tail of the welding symbol.

Any applicable job specification number or code reference may be incorporated into the tail of a welding symbol. In addition, consumable insert class and backing or spacer material specification and dimensions may be shown. The publication *Standard Symbols for Welding, Brazing, and Nondestructive Examination,* ANSI/AWS 2.4,[6] should be consulted for additional applications of specifications to welding symbols.

Letter designations are used in the tail of a welding symbol to communicate the intended welding or brazing process. The more frequently used welding process designations are listed in Table 8.1. A complete listing of designations for welding, brazing, and allied processes is given in *Standard Symbols for Welding, Brazing, and Nondestructive Examination,* ANSI/AWS A2.4.[7]

Many possible references can be included in the tail of a welding symbol. These include the "TYP" notation for typical welds, a reference to a "back weld" or "backing weld" to clarify the intended sequence of welding, backgouge and CJP references, tolerances for weld size, and references to detail or cross-sectional drawings. The publication *Standard Symbols for Welding Brazing, and Nondestructive Examination,* ANSI/AWS 2.4,[8] should be consulted for additional uses of references.

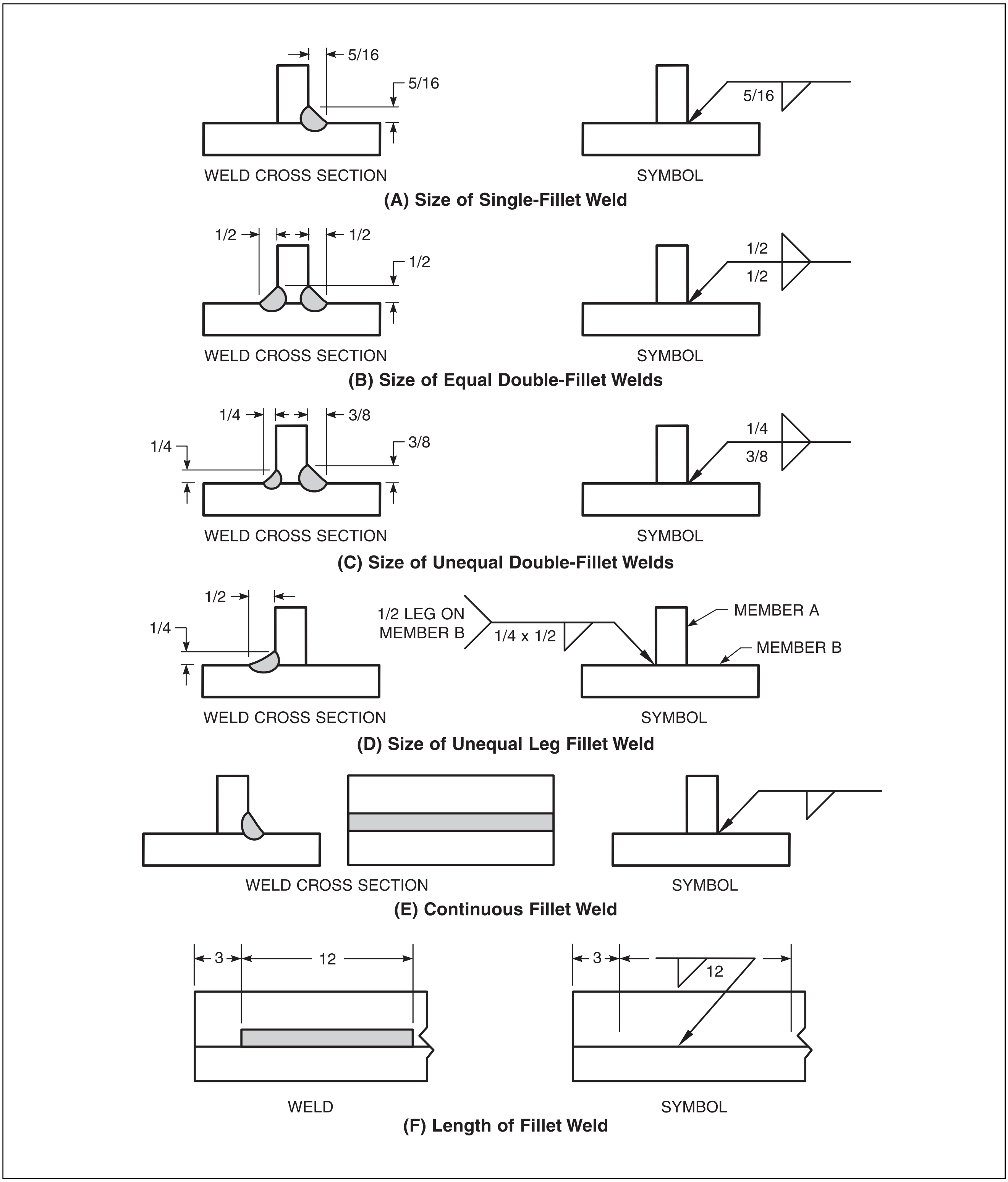
SUPPLEMENTARY SYMBOLS

Supplementary weld symbols complement the basic symbols and provide additional requirements or instructions. Figure 8.12 presents the supplementary symbols that may be used on a welding symbol. Each of these is explained below.

Weld-All-Around Symbol. A weld that extends completely around a series of connected joints is indicated by the weld-all-around symbol. This symbol takes the form of a circle positioned at the junction of the arrow and the reference line. Figures 8.13 illustrates the use of this symbol. In Figure 8.13(A), the weld-all-around symbol indicates that the weld should extend around the entire periphery of the junction between the structural shape and the plate in a typical column-to-base plate connection. In Figure 8.13(B), the weld-all-around symbol indicates that the weld should continue around the entire faying surface of the two workpieces. In Figure 8.13(C), the weld-all-around symbol conveys the fact that the proposed weld occupies more than one plane.

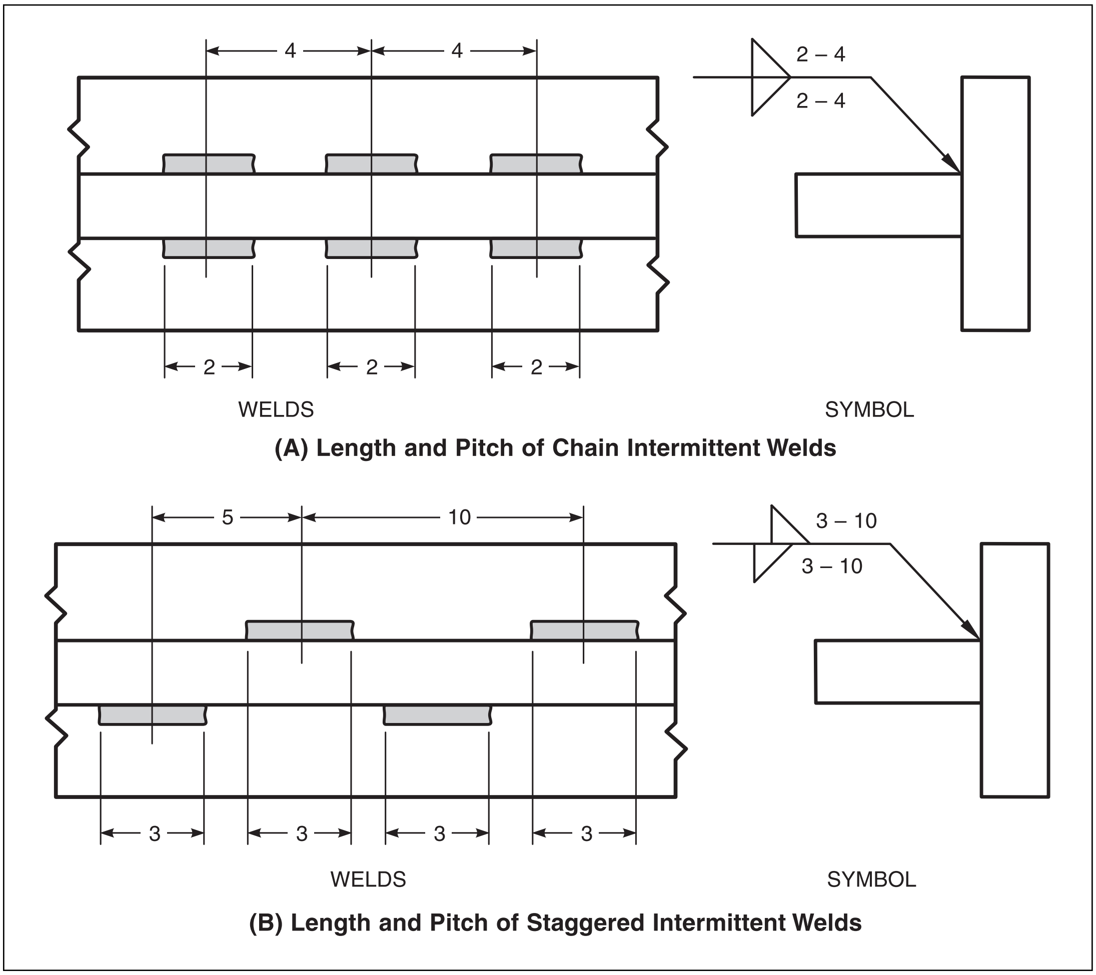
Field Weld Symbol. Field welds are welds that are made at a location such as an installation or erection site, not in a shop or at the place of initial construction. That fact that welds are to be made in the field is communicated by the addition of the field weld symbol to the welding symbol. This symbol takes the shape of a

6. See Reference 2.
7. See Reference 2.
8. See Reference 2.



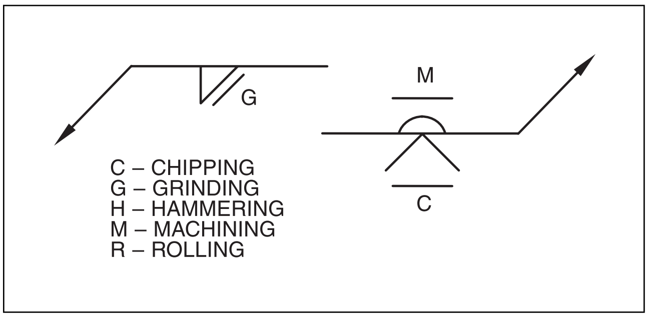
Source: American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 32.

Figure 8.9—Symbols Indicating the Size and Length of Fillet Welds



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 33.

Figure 8.10—Application of Intermittent Fillet Weld Symbols: (A) Length and Pitch of Chain Intermittent Welds and (B) Length and Pitch of Staggered Intermittent Welds

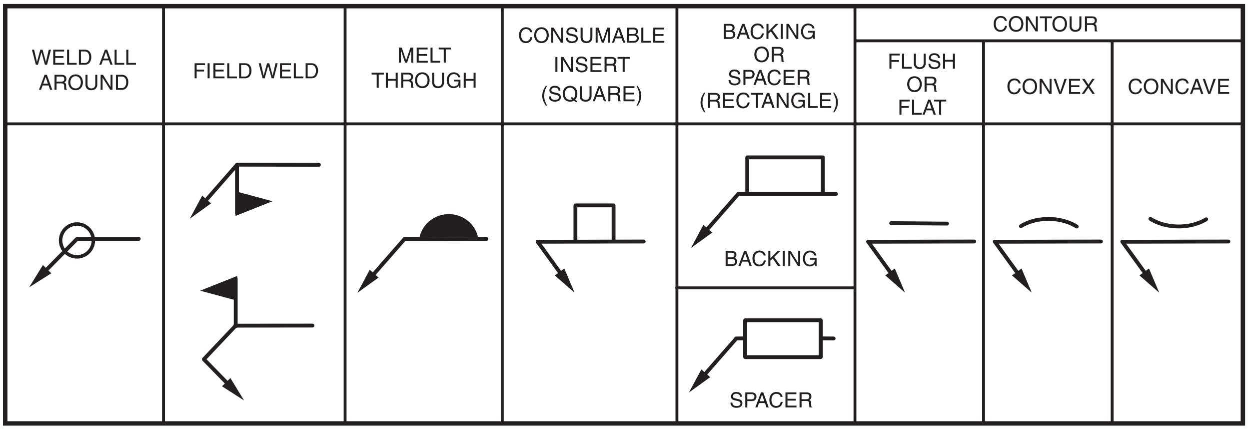


Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 3.13.2, p. 8.

Figure 8.11—Finishing Symbols

Table 8.1
Frequently Used Welding Process Designations

Process	Designation
Shielded metal arc welding	SMAW
Submerged arc welding	SAW
Gas metal arc welding	GMAW
Flux cored arc welding	FCAW
Gas tungsten arc welding	GTAW
Plasma arc welding	PAW
Oxyfuel gas welding	OFW
Electron beam welding	EBW
Laser beam welding	LBW
Resistance spot welding	RSW
Resistance seam welding	RSEW



Source: American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 3.

Figure 8.12—Supplementary Symbols

flag. It may be placed either above or below and perpendicular to the reference line at its junction with the arrow.

Figure 8.14 illustrates the field weld symbol used in conjunction with the weld-all-around symbol, communicating, in this case, that a single-V-groove weld is to be applied along the extent of the weld joint in the field followed by ultrasonic testing (UT) of the entire length of the weld.

Melt-Through Symbol. The melt-through symbol, presented in Figure 8.15, is used to prescribe complete joint penetration (CJP) with visible root reinforcement in welds made from one side. This symbol takes the form of a semicircle. Unlike the back or backing weld symbol shown in Figure 8.17, the melt-through symbol is filled in.

As shown in Figure 8.15(A), the reinforcement is specified by placing the melt-through symbol on the side of the reference line opposite the weld symbol. The height of root reinforcement can be specified to the left of the symbol, as shown in Figure 8.15(B). Control of the root reinforcement height should be consistent with the specified joint design and welding process.

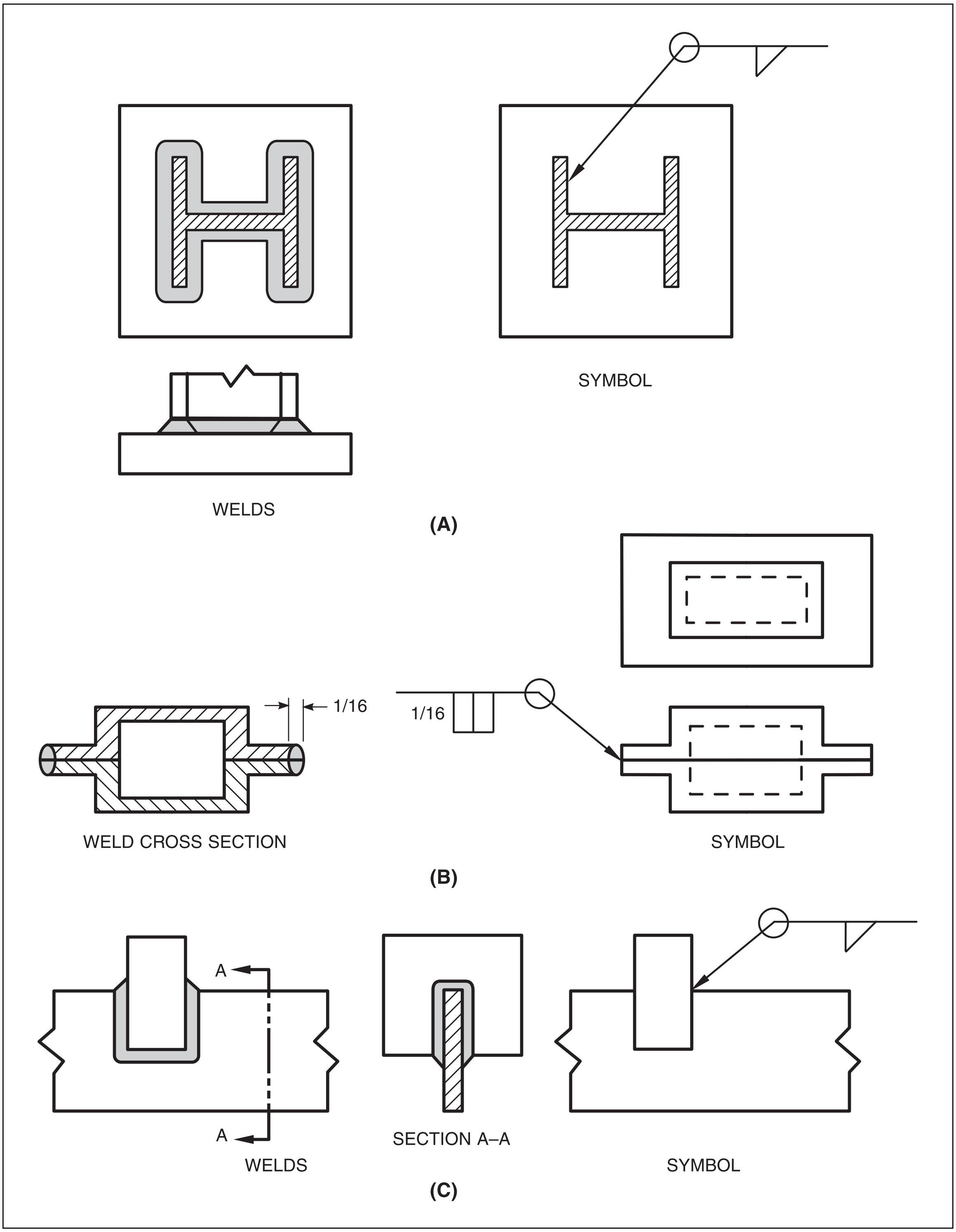
Consumable Insert Symbol. The consumable insert symbol, which takes the form of a square, is placed on the side of the reference line opposite the groove-weld symbol. The AWS classification and the designations for the class and style of the insert are placed in the tail of the welding symbol. This information is obtained from *Specification for Consumable Inserts,* AWS A5.30.[9] Figure 8.16 presents a welding symbol for a typical joint created with a consumable insert.

Backing and Spacer Symbols. A backing symbol is placed above or below the reference line to indicate that a backing ring, strip, or bar is to be used in making the weld. This symbol is used in combination with a groove-weld symbol to avoid interpretation as a plug or slot weld. This figure is drawn using the combination of a groove-weld symbol on one side of the reference line and a backing symbol on the opposite side.

Figure 8.17 presents a welding symbol for a typical joint with backing. As shown in the illustration at the left, the letter "R," signifying "Remove," is placed within the backing symbol to indicate that the backing is to be removed after welding. The backing type, material, and dimensions are specified in the tail of the welding symbol or elsewhere on the drawing, such as in the bill of material that is included with each drawing.

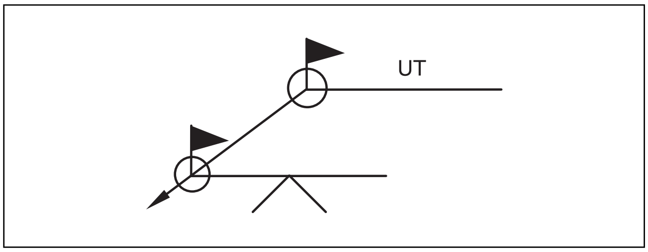
The welding symbol for a joint spacer inserted in the joint root is shown in Figure 8.18. This symbol has the shape of a modified groove-weld symbol with a rectangle incorporated in it. The material and dimensions of the joint spacer are specified in the tail of the welding symbol or elsewhere on the drawing, such as in the bill of material.

9. American Welding Society (AWS) Committee on Filler Metals and Allied Materials, *Specification for Consumable Inserts,* ANSI/AWS A5.30, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 9.

Figure 8.13—Applications of the Weld-All-Around Symbol: (A) Weld-All-Around the Base of a Structural Shape; (B) Weld-All-Around the Edge of Two Halves; and (C) Weld in Several Planes Around the Periphery



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 3.7.3, p. 6.

Figure 8.14—Field Weld Symbol Used in Conjunction with the Weld-All-Around Symbol

Contour Symbol. The contour symbol is used on the weld symbol to indicate the desired shape of the finished weld. The configuration of this symbol therefore differs according to the desired weld shape. Welds that are to be made approximately flat (fillet welds), flush (groove welds), convex, or concave without subsequent finishing are represented by adding the flat, flush, convex, or concave contour symbol to the weld symbol, as shown in Figure 8.19(A). Welds that are to be finished by mechanical means are depicted by adding the symbol for the desired finishing technique to the appropriate contour symbol, as shown in Figure 8.19(B).

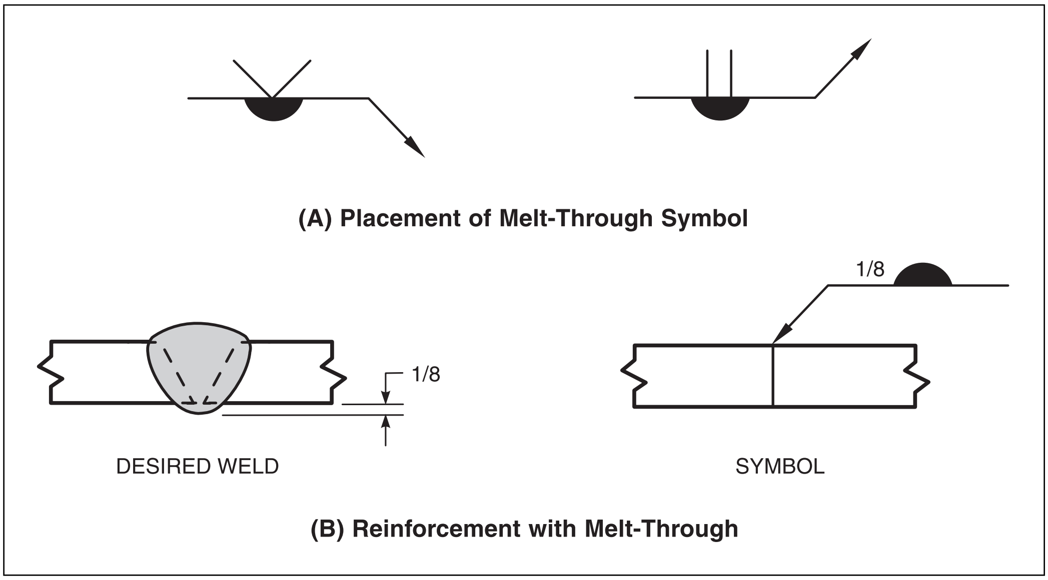
ORIENTATION OF SPECIFIC WELD SYMBOLS

The symbols for bevel-groove, J-groove, flare-bevel-groove, fillet, and corner-flange welds are oriented with the perpendicular leg always to the left. When only one member of a joint is to have the desired edge shape, the arrow points with a definite break toward that member. When the preparation is obvious or the beveling of one member or the other is optional, the arrow need not be broken.

These features are illustrated in Figure 8.20. In the upper weld symbol, the broken arrow points to the member requiring the single-J edge shape. A single-J-groove weld is required on the other side of the joint, furthest from the arrow. In the center symbol, a fillet weld is required on the other side of the joint. The lower welding symbol specifies a double-bevel-groove weld. The broken arrow points to the member that is to be beveled.

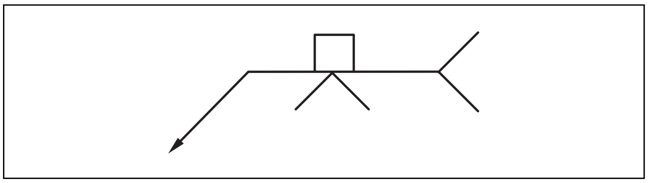
WELD DIMENSION TOLERANCE

When weld dimension tolerances are required, these are noted in the tail of the welding symbol, as shown in Figure 8.21. The notation includes a reference to the dimension to which it applies. Alternatively, the toler-



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 11.

Figure 8.15—Melt-Through Symbol



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 4.10, p. 27.

Figure 8.16—Welding Symbol with a Consumable Insert Symbol and Insert Classification in the Tail

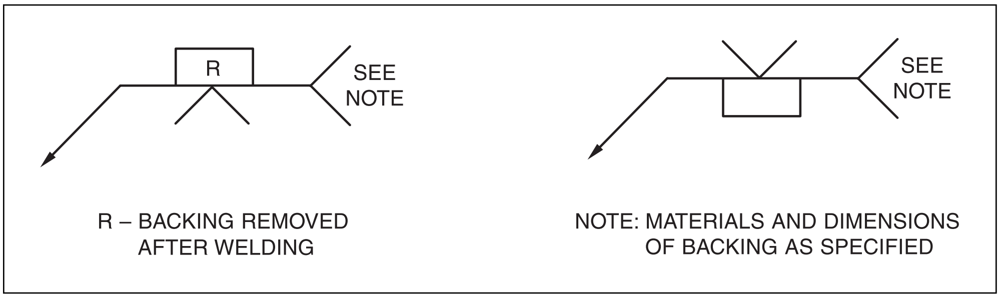
ance may be indicated by a drawing note, code, or specification.

COMBINATIONS OF SYMBOLS

When a combination of welds is to be specified to make a joint, the weld symbol for each weld is placed in the welding symbol, as shown in Figure 8.22. The upper illustration in Figure 8.22 requires a single-V-groove weld from the other side of the joint and a back or backing weld from the arrow side of the joint. The center illustration specifies a single-bevel-groove weld on the arrow side of the joint, with the broken arrow pointing to the member that receives the single-bevel edge shape. The other side of the joint is to receive a fillet weld. The lower welding symbol calls for a single-bevel-groove weld from the other side of the joint. The broken arrow points to the member to be beveled. This groove weld is reinforced with a fillet weld. The arrow side of the joint receives only a fillet weld.

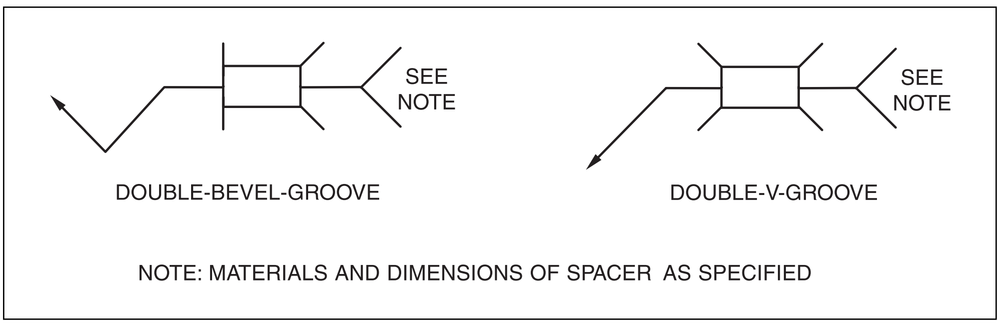
WELDING SYMBOLS FOR SPECIFIC WELD TYPES

This section illustrates the use of welding symbols for common types of welds. Weld types discussed include groove, fillet, plug, slot, spot, projection, seam, stud, and edge welds.



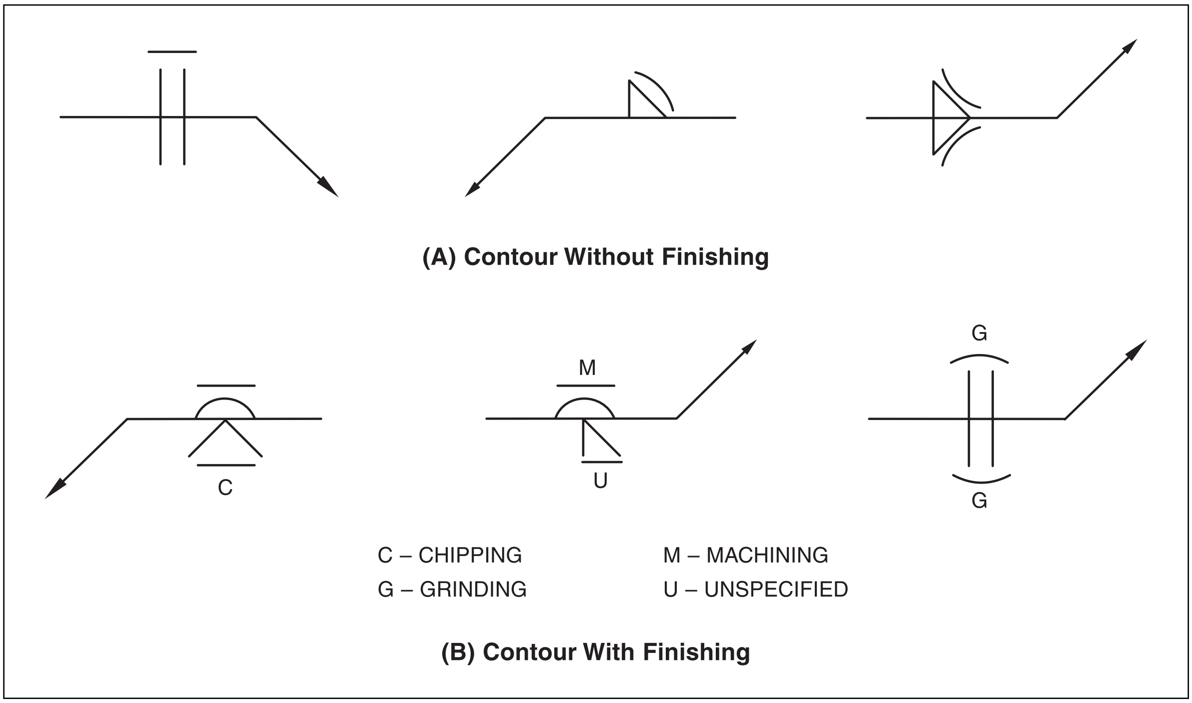
Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 4.8, p. 26.

Figure 8.17—Backing Symbol



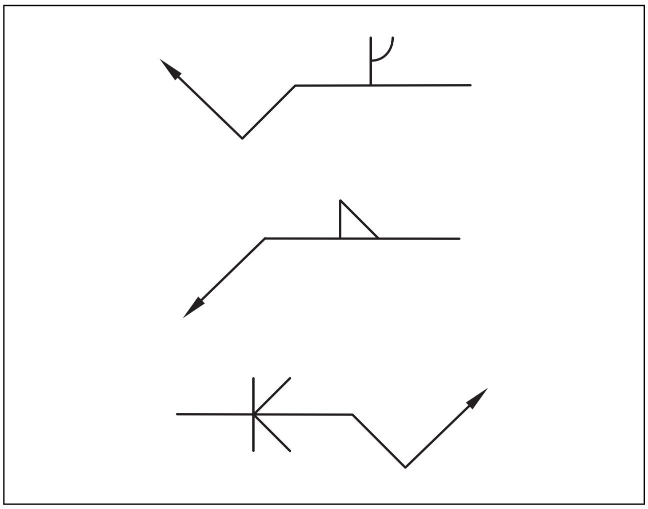
Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 4.9, p. 26.

Figure 8.18—Spacer Symbol



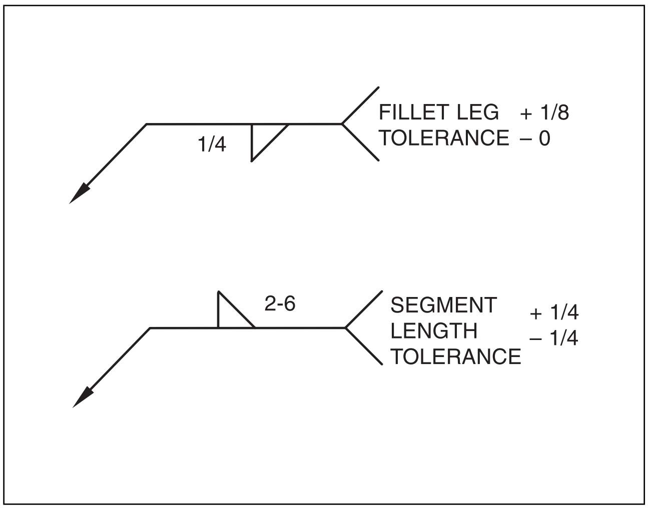
Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraphs 4.6.1, 4.6.2, and 5.6.1, pp. 25, 51.

Figure 8.19—Contour Symbol: (A) Without Finishing and (B) With Finishing



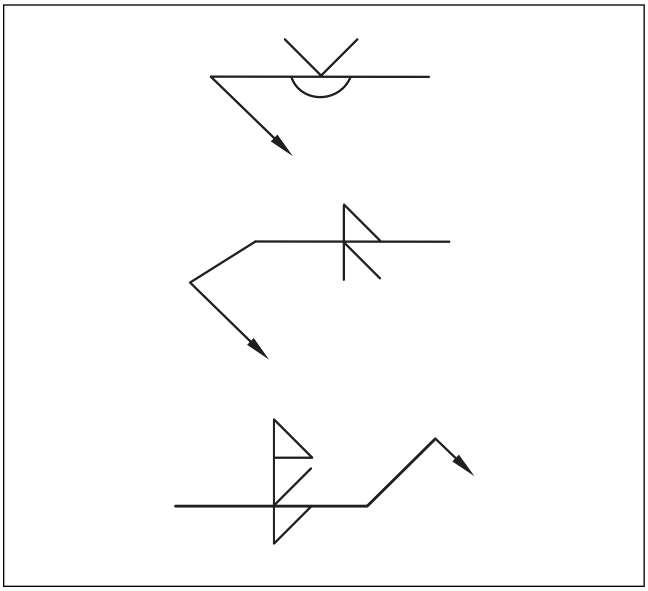
Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraphs 3.2.2 and 3.4, p. 5.

Figure 8.20—Representative Welding Symbols Indicating Only One Side of the Joint Is to Have a Special Edge Shape



Source: American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 3.18, p. 8.

Figure 8.21—Weld Dimension Tolerance



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraphs 3.2.3.2, 3.5, and 4.7.2, pp. 5, 25.

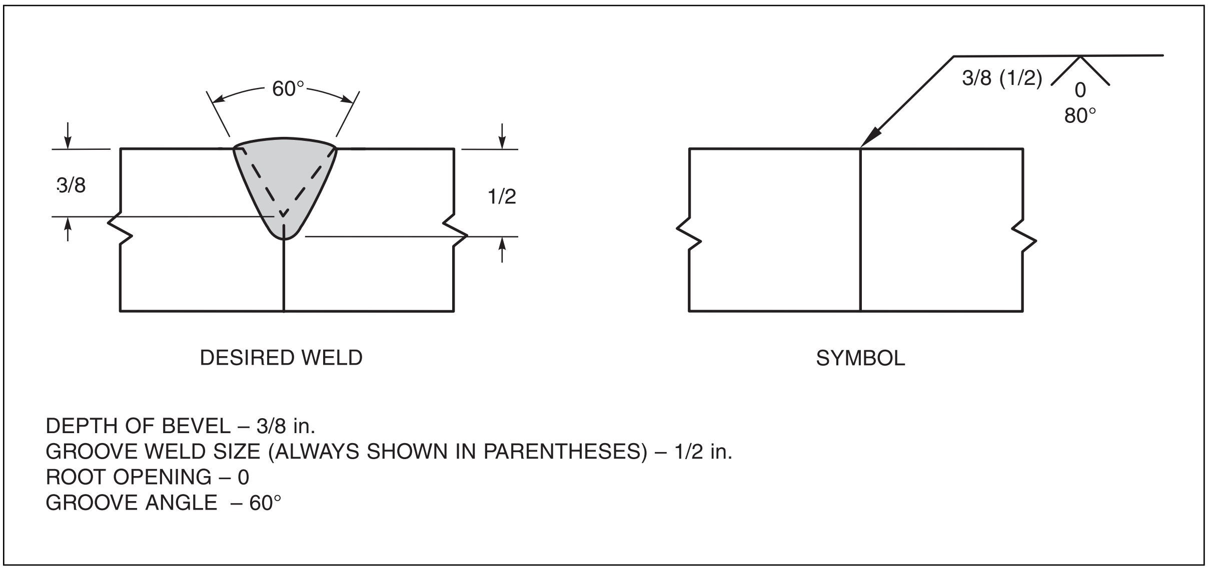
Figure 8.22—Combined Weld Symbols

Groove Welds

In a single-V-groove weld, both members are beveled equally to form a groove at the joint. Figure 8.23 depicts a single-V-groove weld and the appropriate welding symbol. This arrow-side groove weld is of the partial-joint-penetration type since the size of the groove weld is less than the material thickness. The size of the groove weld is greater than the depth of the bevel; therefore, the root penetration must extend 1/8 in. into the joint root.

If a V-shaped groove is required on both sides of the joint, the weld is a double-V-groove type. A schematic illustration of this weld and the symbol representing a double-V-groove weld with symmetrical bevels are shown in Figure 8.24. This symbol does not show the depth of bevel; therefore, a joint symmetrical at or about the plate's mid-thickness is required.

When an asymmetrical V-groove geometry is desired, the depth of bevel must be specified, as shown in Figure 8.25. The welding symbol specifies a double-V-groove weld that is asymmetrical about the midline of the member thickness. In this case, the total groove weld size equals the member thickness of 1 in.



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 14(B).

Figure 8.23—Symbol for Single-V-Groove Weld

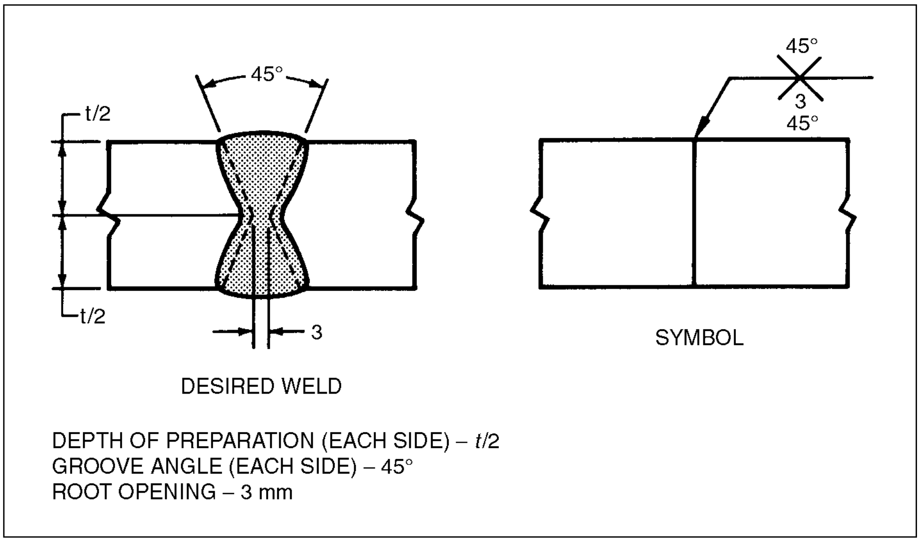
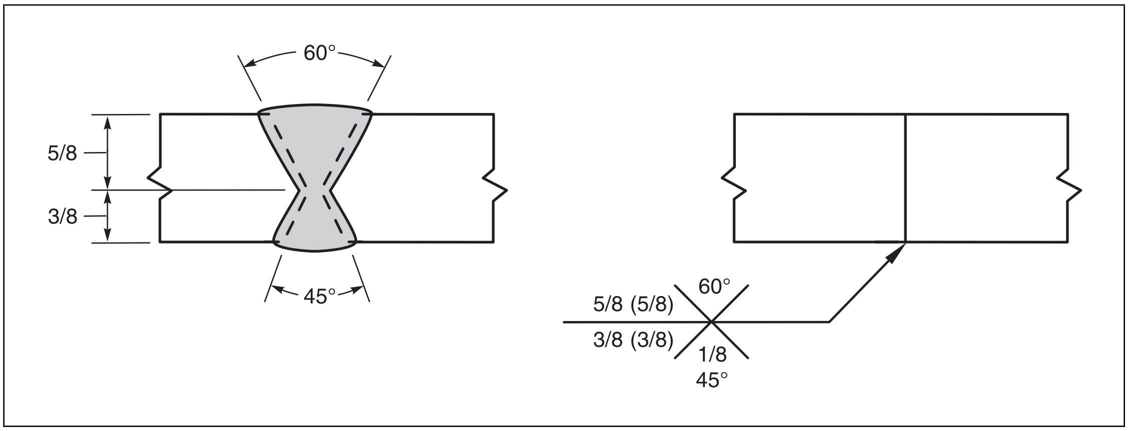


Figure 8.24—Symbol for a Symmetrical Double-V-Groove Weld



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 21(D).

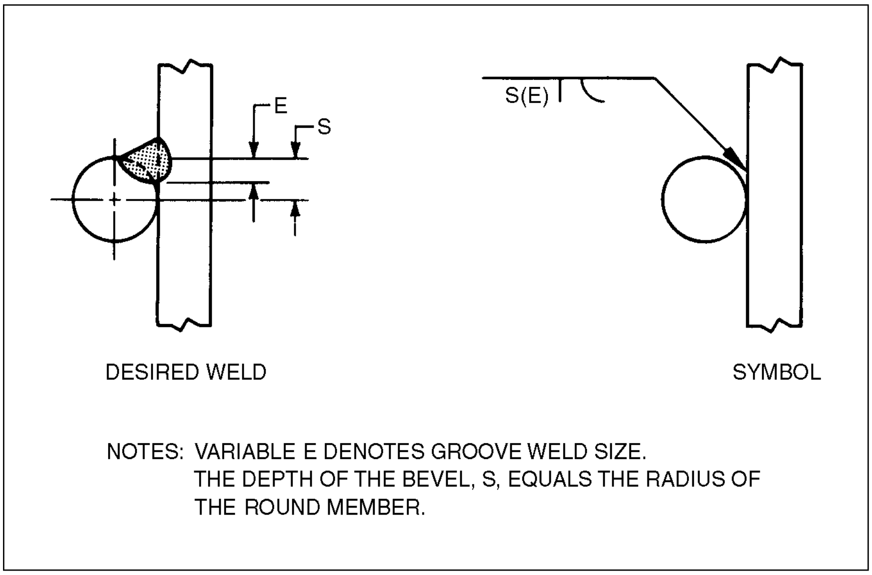
Figure 8.25—Symbol for an Asymmetrical Double-V Groove Weld

A single-flare-bevel-groove weld is made when a round member is placed on a flat surface and a weld is deposited lengthwise along one side. A schematic of such a weld and the appropriate symbol are shown in Figure 8.26. It should be noted that the weld reinforcement is not considered part of the groove weld size.

A single-flare-V-groove is made when two round members are placed side by side and welded together lengthwise. The round shapes may be bent or rolled plates, pipes, or tubes. The weld and the applicable symbol are shown in Figure 8.27. The welding symbol specifies a weld on the other side (furthest from the arrow) of the joint. Weld reinforcement is not considered in the determination of groove weld size.

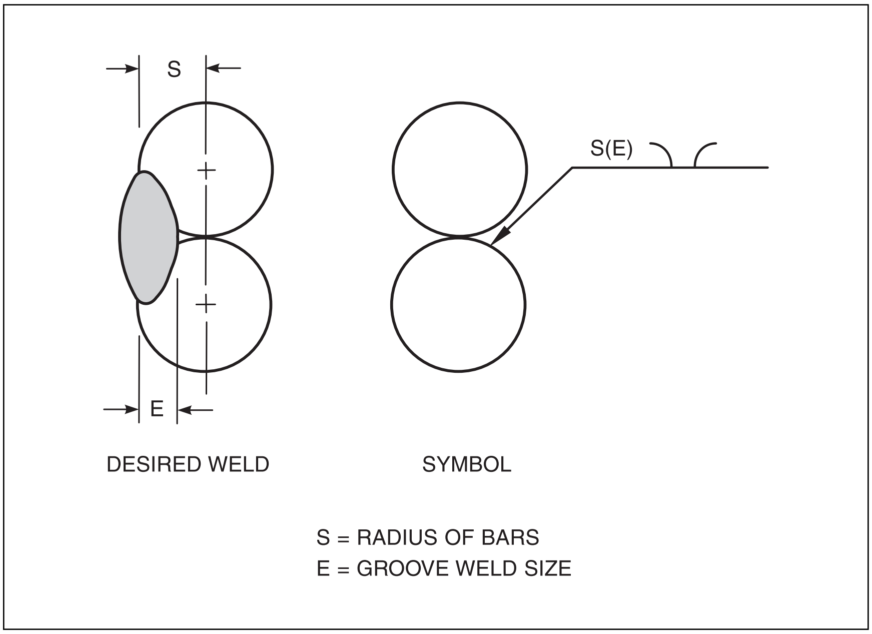
Fillet Welds

A fillet weld has an approximate triangular cross section and joins two surfaces at about 90° to each other. Lap, corner, and T-joints can be joined by fillet welds. When the surfaces to be joined form an angle greater or less than 90°, the weld should be specified with appropriate explanatory details and notes. Fillet welds also



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 20(A).

Figure 8.26—Symbol for Single-Flare-Bevel Groove Weld



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 20(C).

Figure 8.27—Symbol for Single-Flare-V-Groove Weld

are used in conjunction with groove welds as reinforcement in T- and corner joints.

Schematics of fillet welds and examples of the fillet weld symbol are shown in Figure 8.28. In Figure 8.28(A), a 5/16 in. fillet weld is required on the arrow side of the joint. The legs of this weld are required to be 5/16 in. in size. Figure 8.28(B) shows a welding symbol for an unequal leg fillet weld. For this type of fillet weld, the welding symbol does not specify the orientation of the fillet weld, so this must be shown elsewhere on the drawing.

Plug and Slot Welds

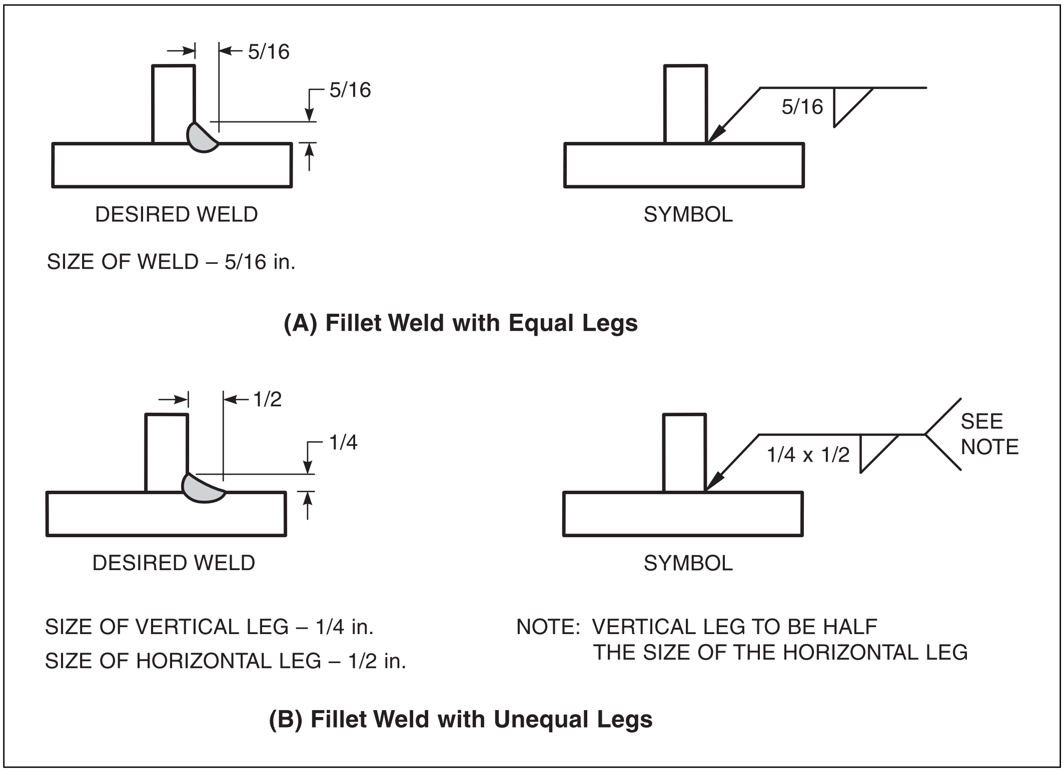
Plug and slot welds are similar in design, but slot welds are elongated in one direction. In both cases, a hole or slot is made in only one member of the workpiece. These welds are not to be confused with fillet welds in a hole because both plug and slot welds require uniform depths of filling.

Although dimensions for the weld size (i.e., the diameter at the faying surface), angle of countersink, depth of fill, and pitch (i.e., center-to-center spacing) of plug welds may be expressed on the welding symbol, the location and orientation of plug or slot welds should be specified on the drawing.

Figures 8.29 and 8.30 present schematic illustrations of plug and slot welds, respectively, and their corresponding welding symbols. Figure 8.29 illustrates a line of three plug welds in a 45° countersink hole. In this example, the depth of filling required is less than the depth of the hole. The plug weld size, measured at the faying surface is 1 inch (in.). Figure 8.30 shows a line of two slot welds. The slots are not completely filled with weld metal, and no countersink is required. The width of the slot welds is 3/4 in. at the faying surface.

Spot Welds

A spot weld is made between or upon overlapping members in which coalescence may begin and continue



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 32(D).

Figure 8.28—Symbol for Fillet Welds: (A) Weld with Equal Legs and (B) Weld with Unequal Legs

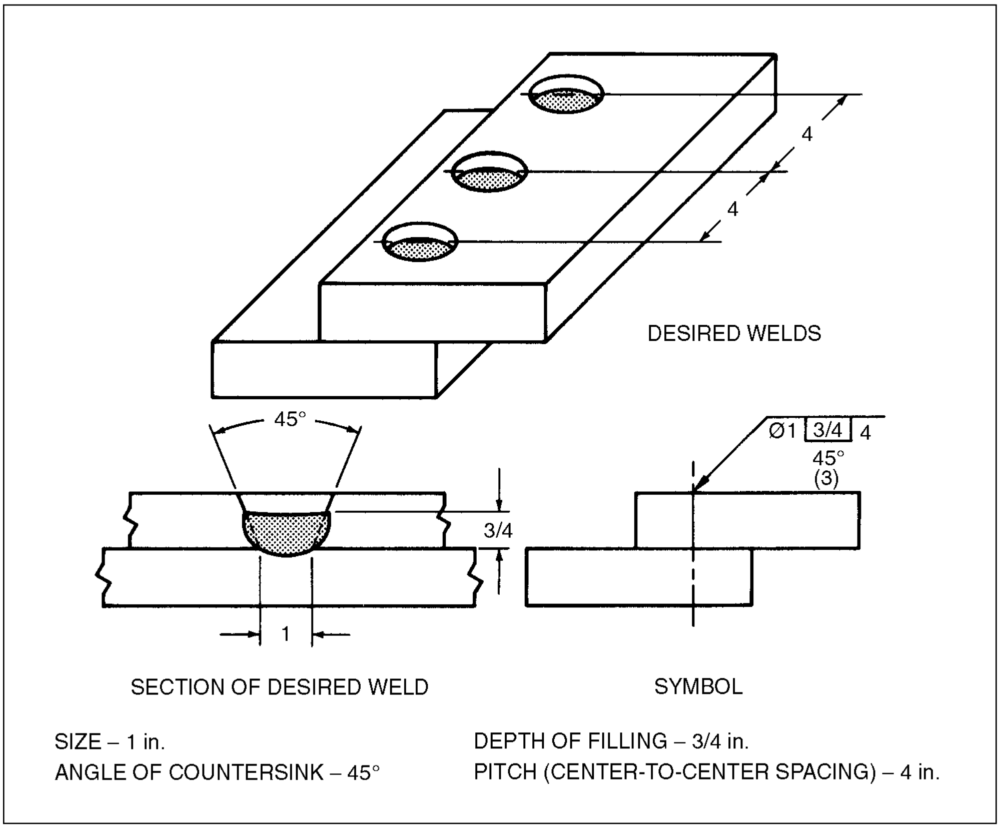


Figure 8.29—Symbol for a Plug Weld

over the faying surfaces or may proceed from the surface of one member. The weld cross section (plan view) is approximately circular. Fusion welding processes that have the capability of melting through one member of a joint and fusing with the second member at the faying surface can be used to make spot welds. Resistance welding equipment can also be used.

Schematic illustrations of arc and resistance spot welds are shown in Figure 8.31, together with the proper welding symbols. Figure 8.31(A) shows a welding symbol for a line of nine arc slot welds to be made with the gas tungsten arc welding process from the arrow side of the joint. The spot welds are spaced at 2 in. center to center and have a diameter of 0.25 in. at the faying surfaces. The drawings specify the orientation of the slot welds.

In Figure 8.31(B), the welding symbol specifies a line of five resistance spot welds. The welds have a diameter of 0.25 in. at the faying surfaces and are spaced at 1 in. center to center. The drawing specifies the location of the first spot weld in the line. Since the resistance spot welding process has no arrow or other side significance, the weld symbol is centered on the reference line.

Projection Welds

The weld symbol for projection welds is the same as that for spot welds, except that the symbol is placed above or below the reference line to specify the member to be embossed. The process is indicated in the tail of the welding symbol. A schematic illustration of a resistance projection weld and its corresponding welding symbol are presented in Figure 8.32.

Seam Welds

A seam weld is a continuous weld made between or upon overlapping members. Coalescence may start and occur on the faying surfaces, or may proceed from the surface of one member. The continuous weld may be a

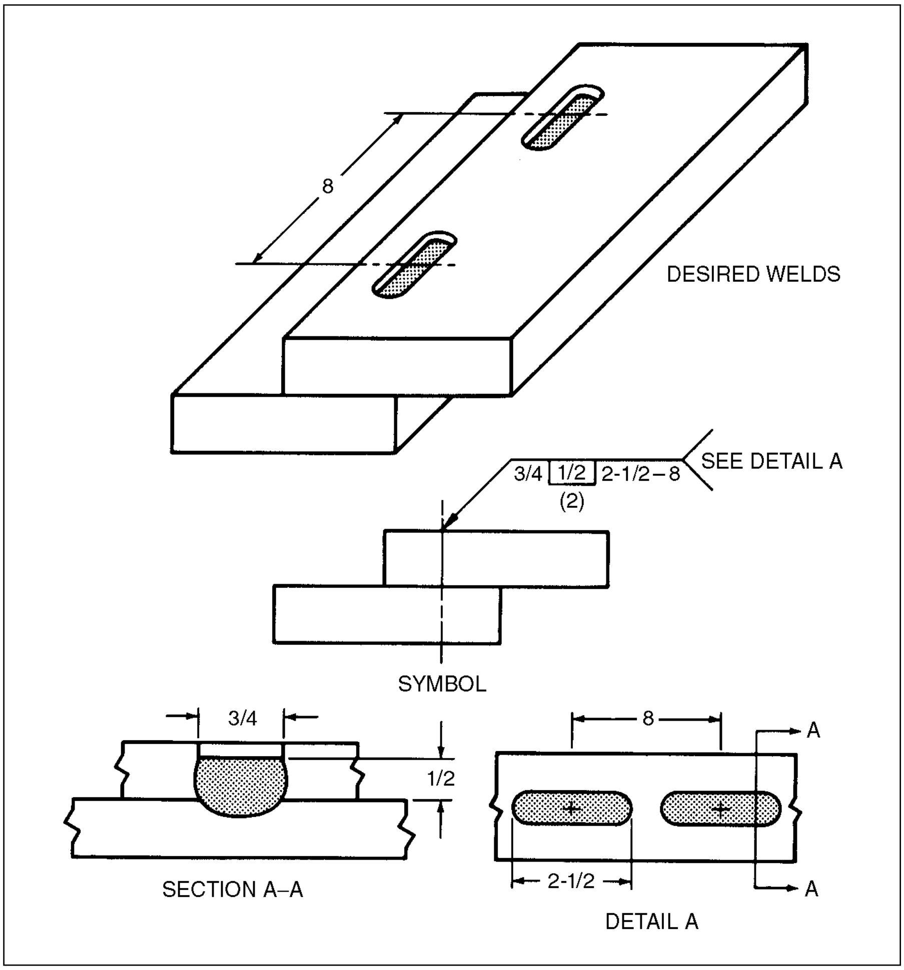


Figure 8.30—Symbol for a Slot Weld

single weld bead or a series of overlapping spot welds. Seam welds are made with processes and equipment similar to those used for spot welding. A means of moving the welding head along the seam must be provided. Examples of arc and resistance seam welds and their appropriate welding symbols are shown in Figure 8.33.

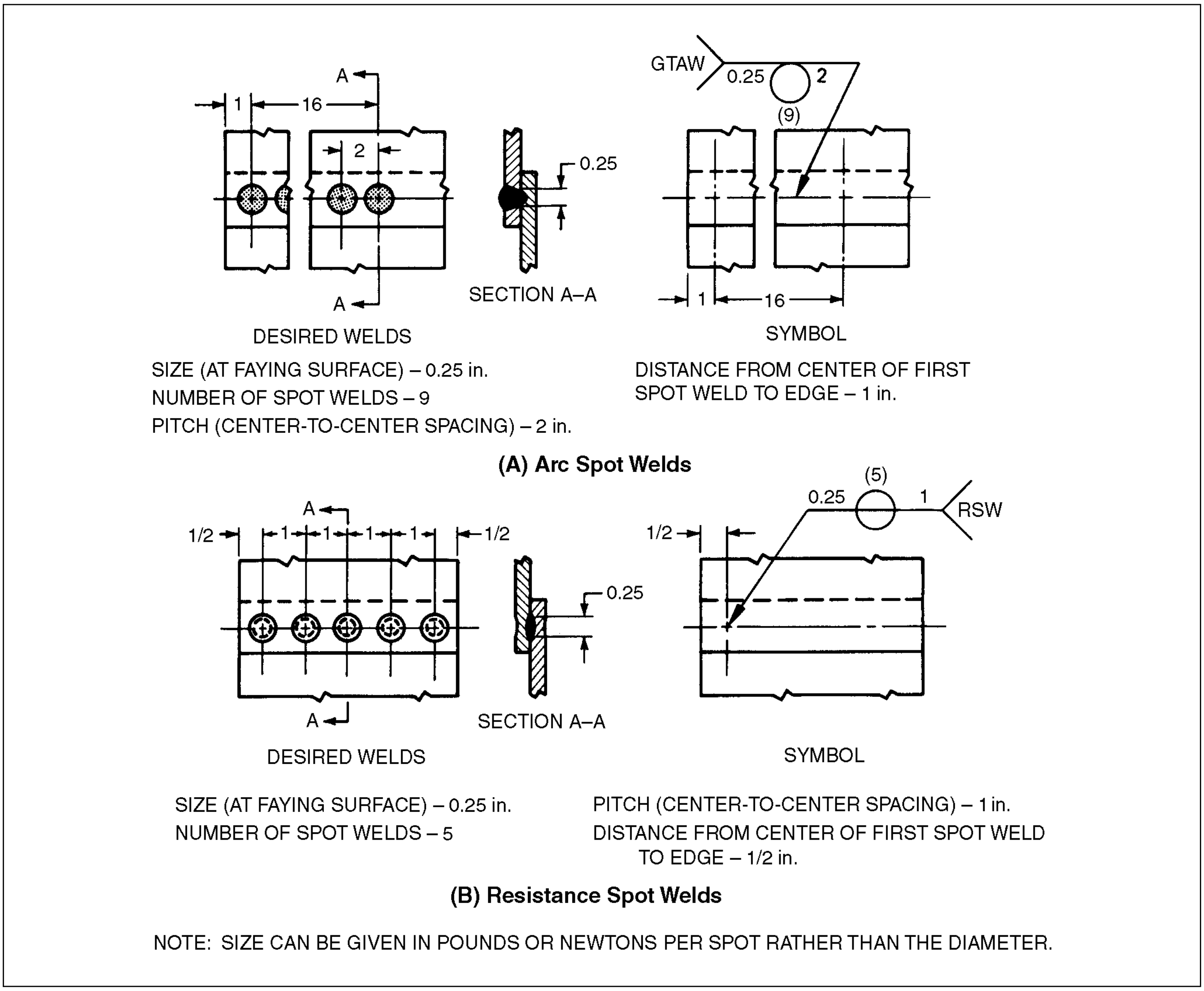
Stud Welds

The weld symbol for stud welds is similar to that for spot welds except that the circle contains a cross. The symbol is placed below the reference line and the arrow pointed to the surface to which the stud is to be welded. The size of the stud is specified to the left of the weld symbol, the pitch is indicated to the right, and the number of stud welds is placed below the symbol in parentheses. Dimensions for the spacing of stud welds in any configuration other than a straight line must be stated on the drawing.

Figure 8.34 illustrates the use of the stud weld symbol. The welding symbol specifies three lines of seven studs each. The studs, which are 3/4 in. in diameter, are spaced in each line at 4 in. from center to center. The orientation of this grouping of studs is explained by the drawing.

Edge Welds

The edge weld symbol is used when the full thickness of the joint members in edge joints, flanged butt joints,



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figures 40(D) and (F).

Figure 8.31—Symbol for Spot Welds: (A) Arc Spot Welds and (B) Resistance Spot Welds

or flanged corner joints are to be fused. Figure 8.35 presents several examples.

BRAZING SYMBOLS

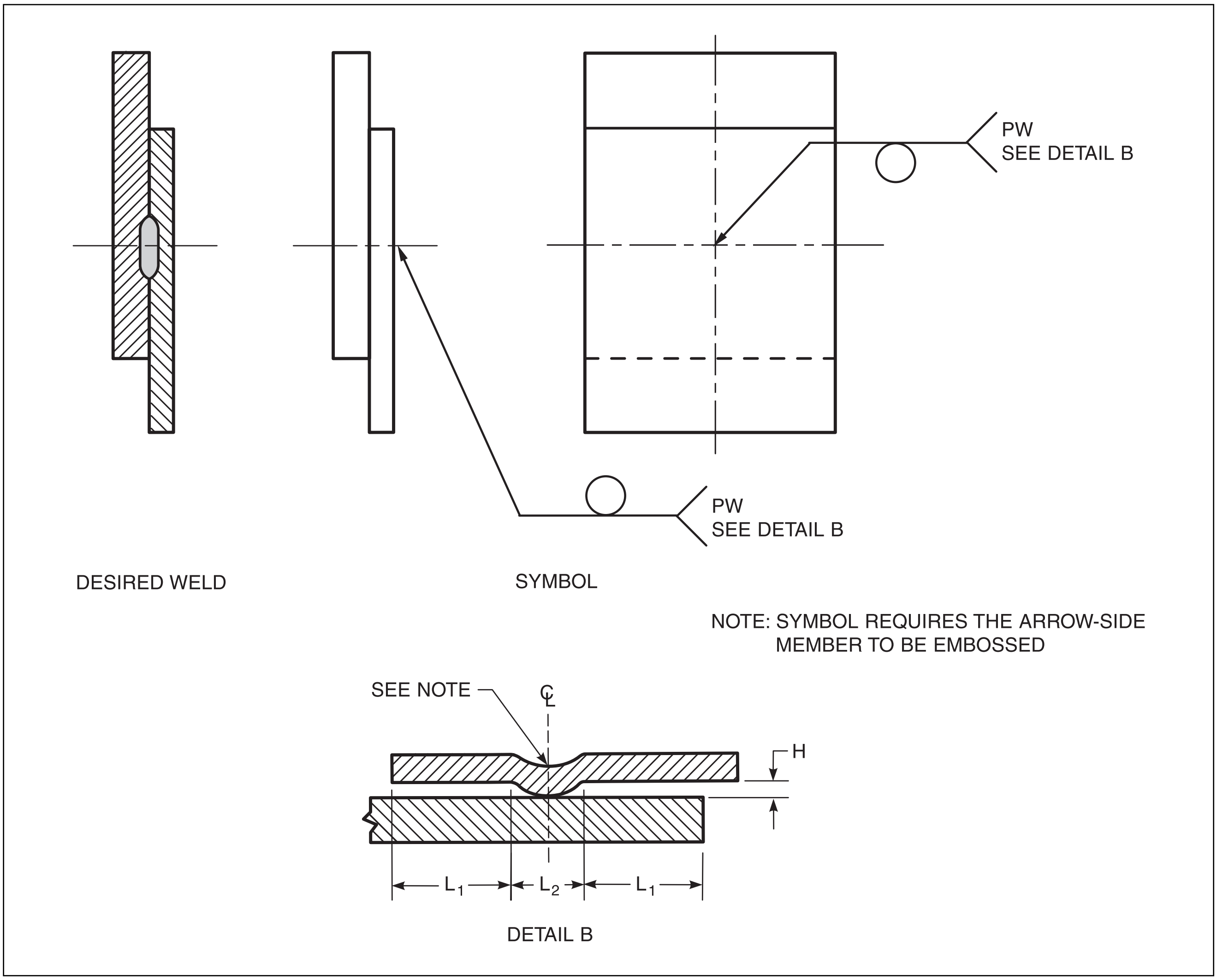
The symbols for brazing have the same basic structure as welding symbols. The clearance between the members may be specified in a similar manner to that used for root openings with welding symbols.

LETTER DESIGNATIONS FOR BRAZING PROCESSES

The brazing processes used in construction can be designated by letters. The brazing processes and their corresponding letter designations are presented in Table 8.2.

BRAZED JOINTS

When no special preparation other than cleaning is required for the production of a brazed joint, the arrow



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 41(A).

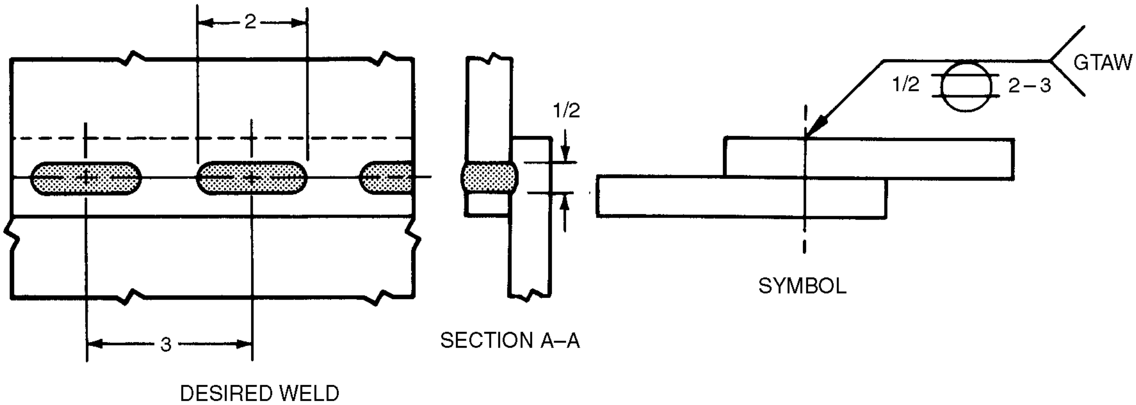
Figure 8.32—Symbol for Resistance Projection Welds

and reference line are used with the brazing process indicated by placing the process designation in the tail. Figure 8.36 shows a sketch and accompanying symbol depicting a brazed socket joint.

The application of conventional weld symbols to brazed joints is illustrated in Figures 8.37(A) through 8.37(F). Figure 37(A) shows the desired scarf configuration and the dimensions of a brazed joint on the left and the corresponding brazing symbol on the right. Figure 8.37(A) also shows the method of specifying a scarf angle. Figures 8.37(A), (B), (C), (D), and (F) demonstrate the manner in which joint clearance dimensions can be incorporated into a brazing symbol.

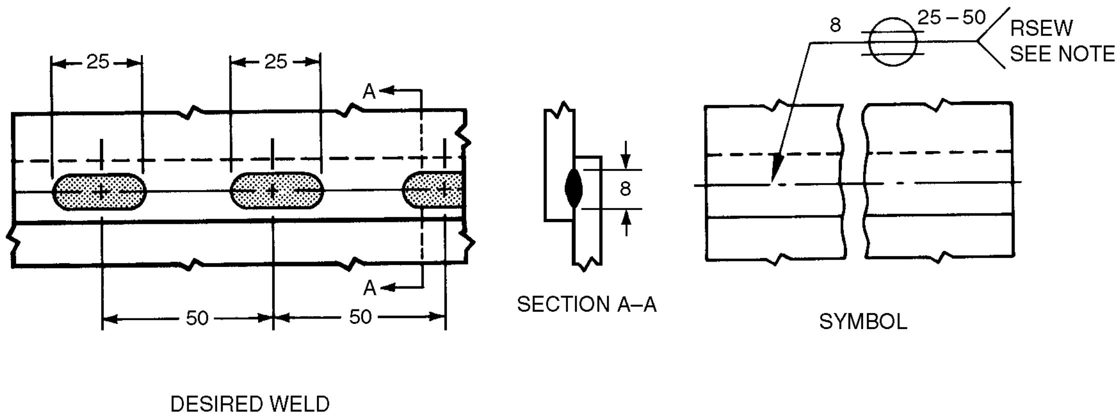
SOLDERING SYMBOLS

The symbols used for soldered joints have the same basic structure as those used for welding. When no special preparation other than cleaning is required for the



SIZE (AT FAYING SERVICE) – 1/2 in.
LENGTH – 2 in.
PITCH (CENTER-TO-CENTER SPACING) – 3 in.

(A) Arc Seam Weld



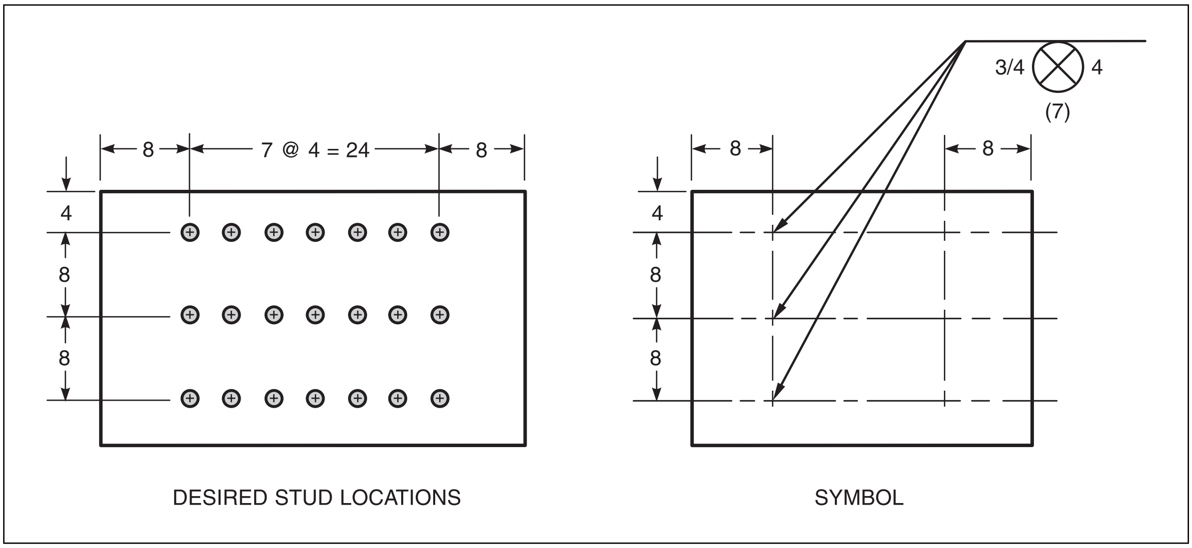
SIZE (AT FAYING SURFACE) – 8 mm
LENGTH – 25 mm
PITCH (CENTER-TO-CENTER SPACING) – 50 mm

(B) Resistance Seam Weld (SI Units)

NOTE: AS AN ALTERNATIVE TO WELD SIZE, STRENGTH MAY BE GIVEN IN POUNDS PER LINEAR INCH OR NEWTONS PER MILLIMETER.

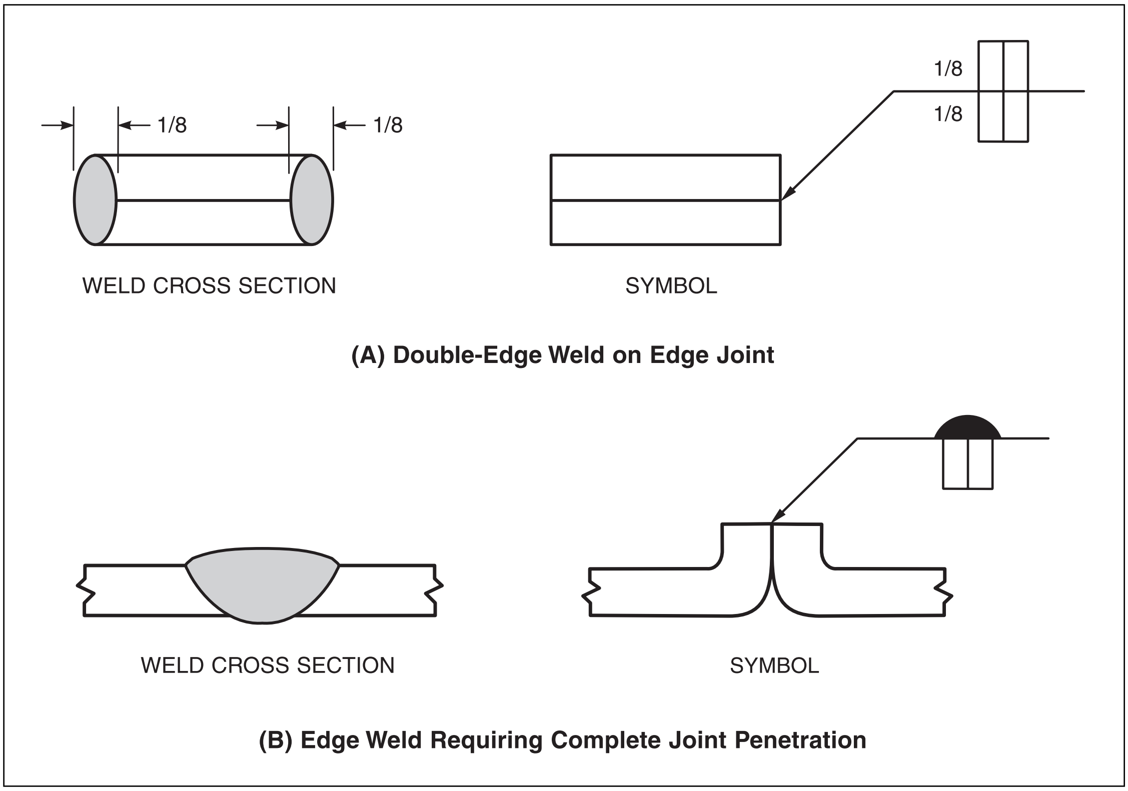
Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 44.

Figure 8.33—Symbols for Seam Welds



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 47(B).

Figure 8.34—Symbol for Stud Welds



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figures 46(A) and (E).

Figure 8.35—Applications of Edge Weld Symbols

Table 8.2
Letter Designations for Brazing Processes

Process	Designation
Block brazing	BB
Carbon arc brazing	CAB
Dip brazing	DB
Exothermic brazing	EXB
Furnace brazing	FB
Induction brazing	IB
Infrared brazing	IRB
Resistance brazing	RB
Torch brazing	TB

production of a soldered joint, the arrow and the reference line are used with the soldering process indicated by placing the process designation in the tail.

LETTER DESIGNATIONS FOR SOLDERING PROCESSES

The soldering processes and their corresponding letter designations are presented in Table 8.3.

SOLDERED JOINTS

Similar to the symbols for brazing, soldering symbols may incorporate clearance and length of overlap dimensions.

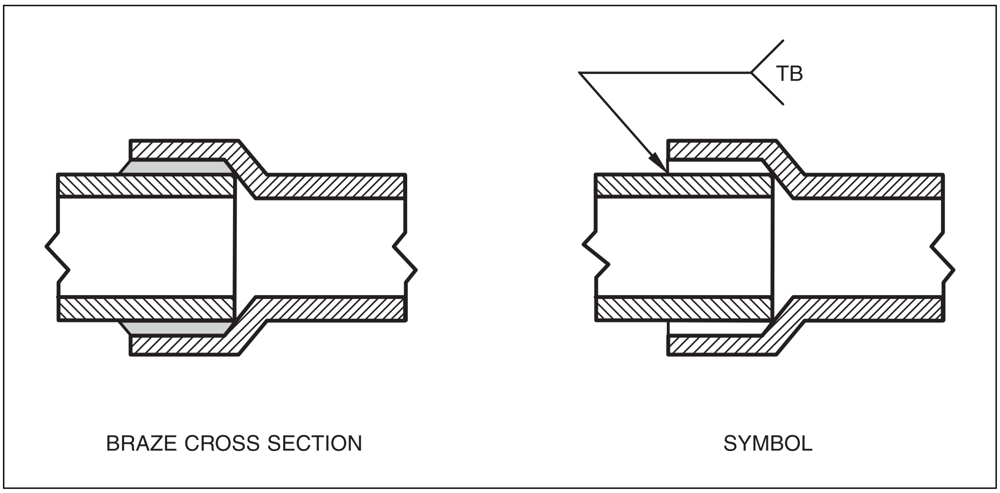
INSPECTION SYMBOLS

On engineering drawings, inspection symbols provide a means for specifying the method of examination to be used. Nondestructive examination symbols (NDE) are specified along with welding symbols by using an additional reference line or by specifying the examination method in the tail of the welding symbol.

ELEMENTS OF INSPECTION SYMBOLS

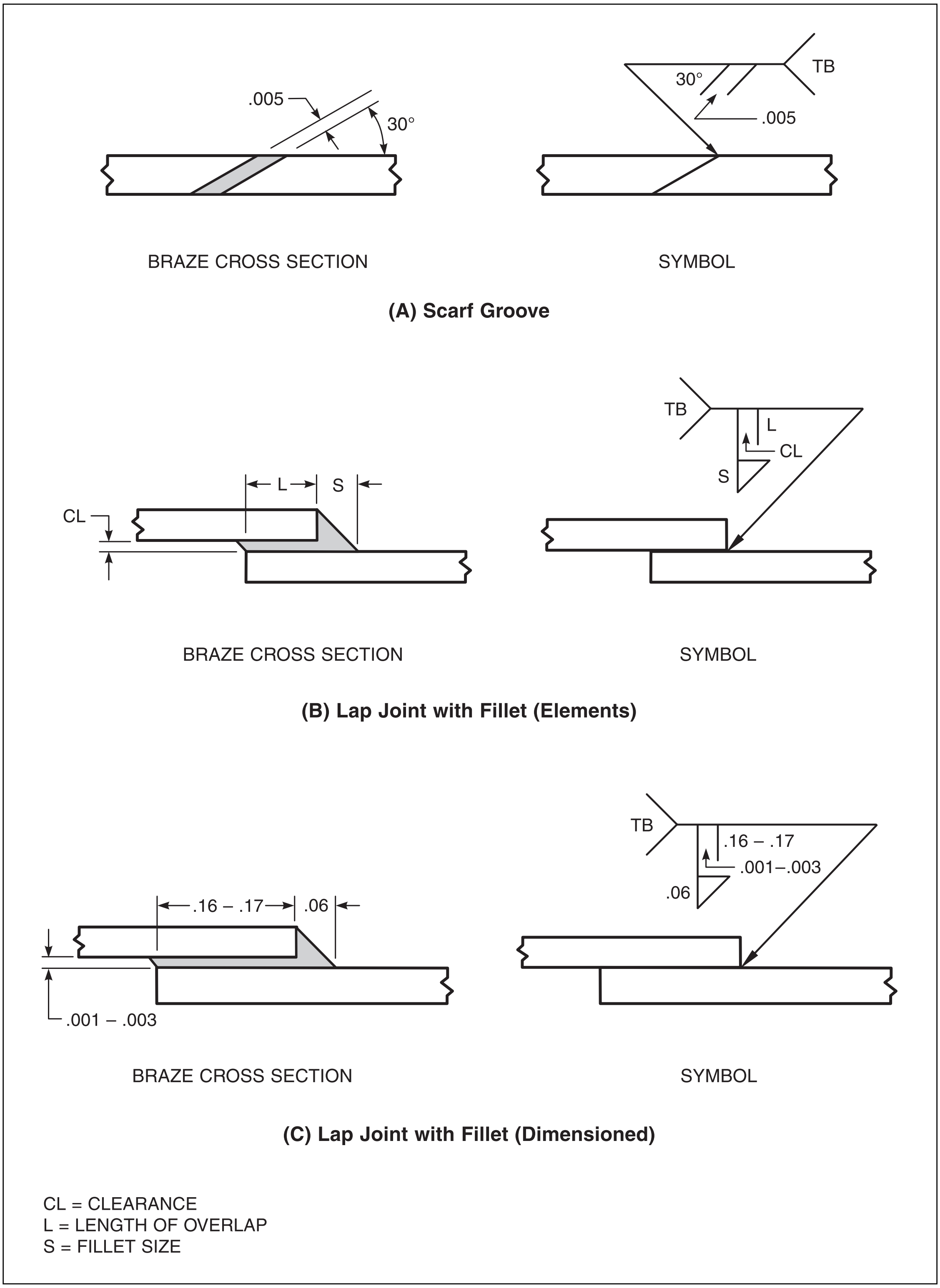
Nondestructive examination symbols are composed of the following elements:

1. Reference line;
2. Arrow;
3. Tail;
4. Examination method letter designations;
5. Extent of examinations;
6. Specifications, codes, and other references; and
7. Supplementary symbols.



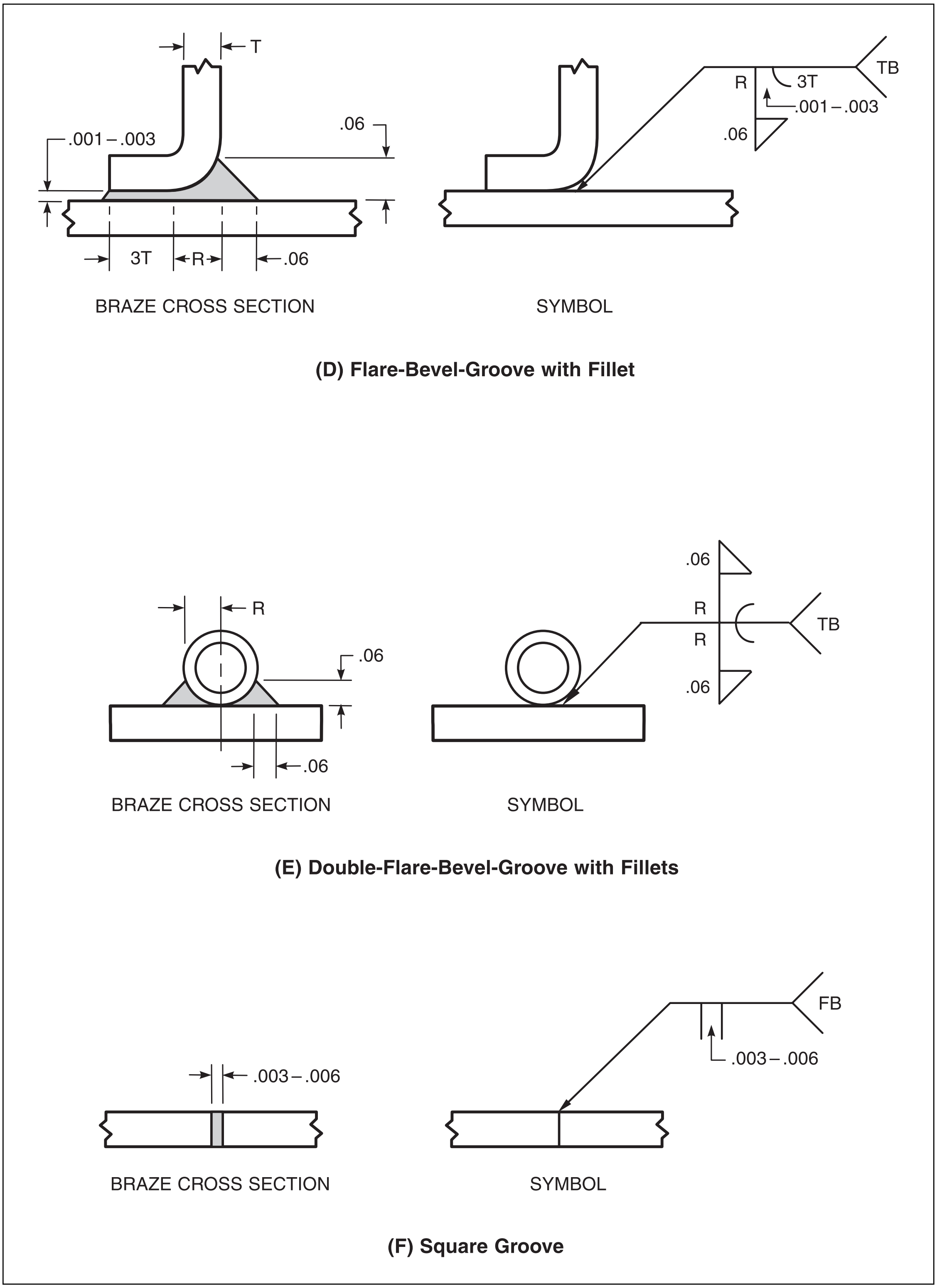
Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 49.

Figure 8.36—Desired Braze and Corresponding Brazing Symbol



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 49.

Figure 8.37—Application of Brazing Symbols



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 49.

Figure 8.37 (Continued)—Application of Brazing Symbols

Table 8.3
Letter Designations for Soldering Processes

Process	Designation
Dip soldering	DS
Furnace soldering	FS
Induction soldering	IS
Infrared soldering	IRS
Iron soldering	INS
Torch soldering	TS
Ultrasonic soldering	USS
Wave soldering	WS

Table 8.4
Nondestructive Examination Letter Designations

Examination Method	Designation
Acoustic emission	AET
Electromagnetic	ET
Leak	LT
Magnetic particle	MT
Neutron radiographic	NRT
Penetrant	PT
Proof	PRT
Radiographic	RT
Ultrasonic	UT
Visual	VT

Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, p. 89.

The elements used in inspection symbols are described in detail below.

Reference Line

The reference line is the basic and required symbol element about which the inspection information is located. The preferred orientation is horizontal.

Arrow

The arrow connects the reference line to the workpiece to be examined. The side of the workpiece to which the arrow points is known as the *arrow side*. The side opposite the arrow side is termed the *other side*.

Tail

When a specification or other reference is needed to convey the requirements of the inspection process, this information is placed in a tail of the symbol. The tail is omitted when no specification or other reference is needed.

Examination Method Letter Designations

The letter designations used to indicate the various nondestructive examination processes are presented in Table 8.4. Figure 8.38 illustrates the locations of these letter designations with respect to the reference line and their corresponding significance. To indicate that examinations are to be performed on the arrow side of a joint, the examination method letter designation symbol is placed below the reference line. Figure 8.38(A) illustrates this convention.

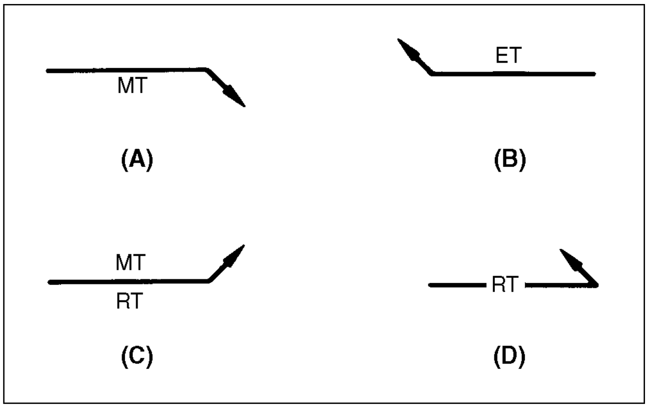


Figure 8.38—Location and Significance of Letter Designations in Brazing Symbols: (A) Examine the Arrow Side; (B) Examine the Other Side; (C) Examine Both Sides; and (D) No Side Significance

Examinations to be made on the other side of the joint are indicated by placing the basic examination symbol above the reference line, as shown in Figure 8.38(B). Examinations to be made on both sides of the joint are indicated by positioning the basic examination symbols on both sides of the reference line, as in Figure 8.38(C).

When the examination can be performed from either side or when no arrow-side or other-side significance exists, the basic examination symbols are centered in the reference line. This arrangement is shown in Figure 8.38(D).

STANDARD LOCATION OF THE ELEMENTS IN THE NONDESTRUCTIVE EXAMINATION SYMBOL

The locations of the elements of the nondestructive examination symbol with respect to one another are standard. These are shown in Figure 8.39.

Extent of the Examination

The conventions used to convey the extent of nondestructive examination are illustrated in Figure 8.40.

Length to Be Examined. To specify that the examination concerns only the length of a section, the desired length is positioned to the right of the NDE symbol. This convention is illustrated in Figure 8.40(A). To show the exact location of a section to be examined as well as its length, appropriate dimensions are included in the drawing, as illustrated in Figure 8.40(B).

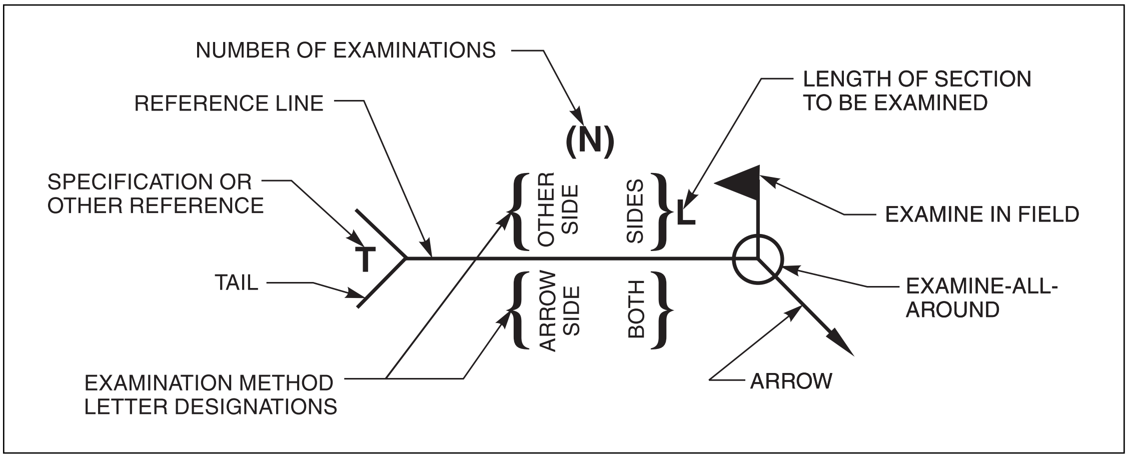
When no length dimension is included in the nondestructive examination symbol, it is understood that the full length of a workpiece is to be examined. When a partial examination of the length of a weld or workpiece is to be prescribed, with the locations determined by a specified procedure, the length to be examined is indicated by placing the appropriate percentage to the right of the letter designation, as illustrated in Figure 8.40(C).

Number of Examinations. Standard conventions are also used to indicate the number of examinations to be performed. When several examinations are to be made on a joint or part at random locations, the number of examinations is given in parentheses either above or below the letter designation, as shown in Figure 8.40(D). If no number is specified, only one examination is to be conducted.

Figure 8.40(E) illustrates the use of the examine-all-around symbol to indicate that complete examination is to be made of a continuous joint, such as a circumferential pipe joint.

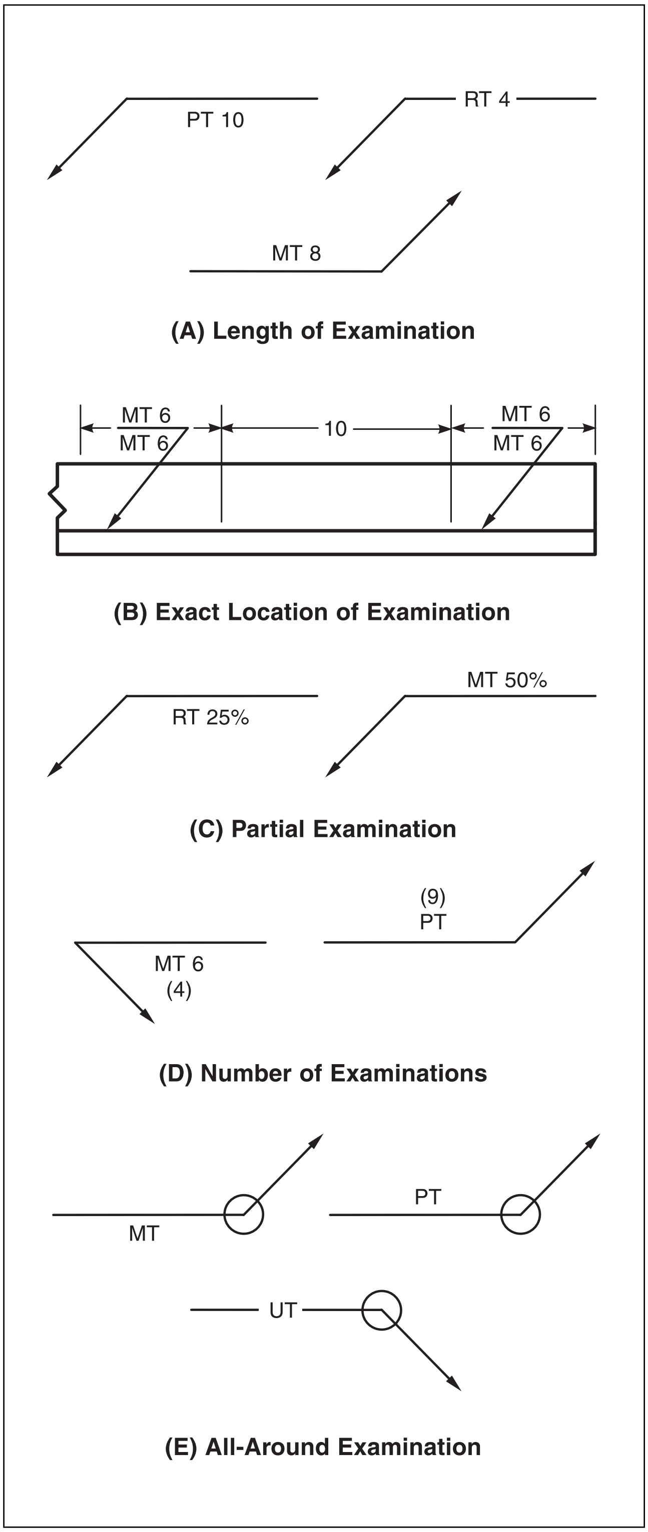
Area to Be Examined. The nondestructive examination of specific areas of a workpiece is prescribed using various methods. These conventions are illustrated in Figure 8.41. To specify that a plane area is to be examined, the target area is indicated on the drawing by enclosing it with straight broken lines and placing a circle at each change of direction. The method of nondestructive examination to be employed in the enclosed area is designated with the appropriate letter designation, as shown in Figure 8.41(A). The area may be located by coordinate dimensions, which would be shown on the drawing.

When the nondestructive examination of areas of revolution is to be performed, the area to be examined is indicated by using the examine-all-around symbol and the appropriate dimensions. For example, the upper symbol used in Figure 8.41(B) indicates that the bore of the hub is to be inspected using magnetic particle



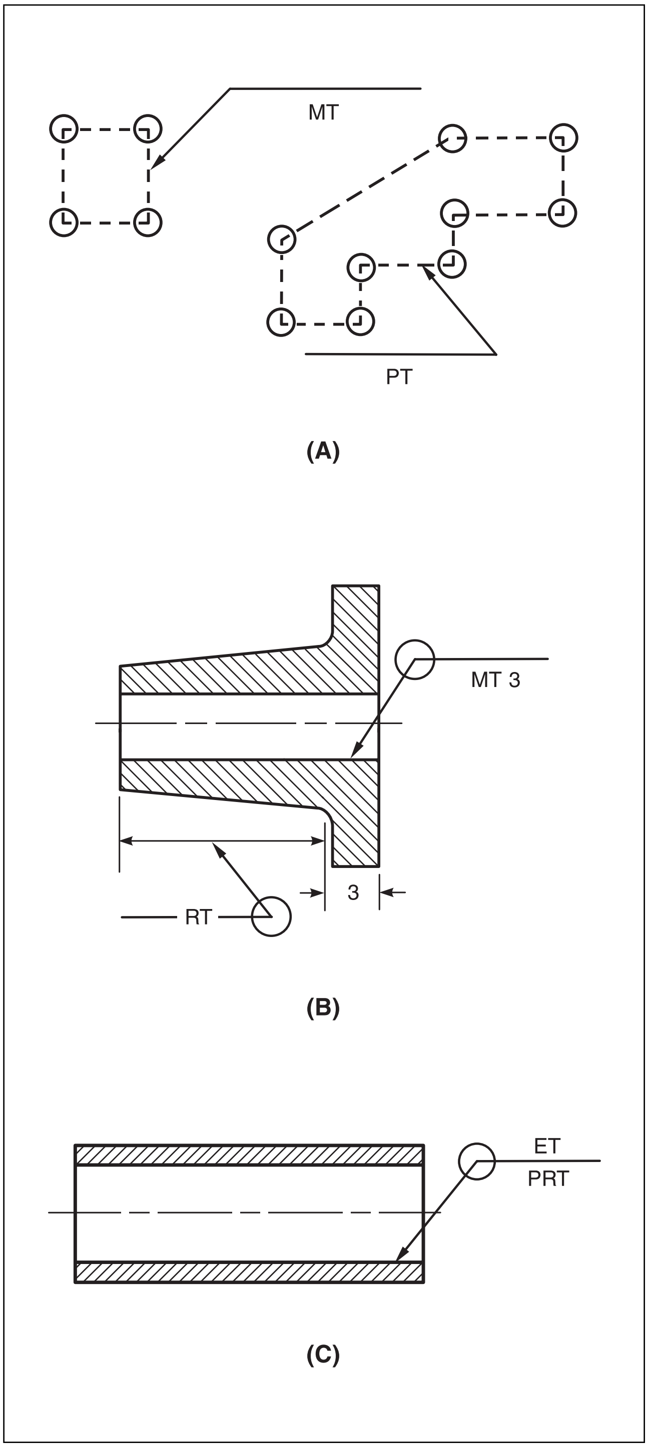
Source: American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Figure 50.

Figure 8.39—Standard Location of the Elements in the Nondestructive Examination Symbol



Source: Adapted from AWS Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing and Nondestructive Examination*, ANSI/AWS A2.4-98, Paragraphs 16.1, 18.1, and 18.2, pp. 91–92.

Figure 8.40—Extent of Examination



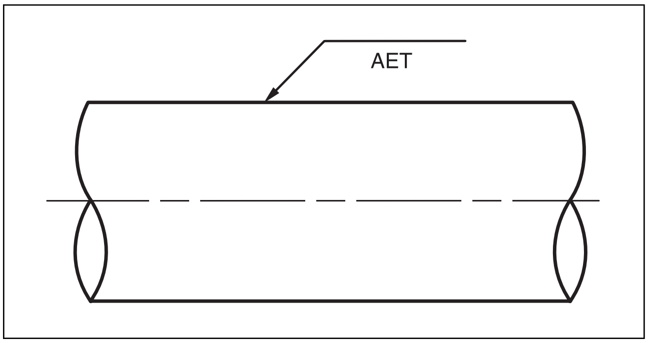
Source: Adapted from AWS Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing and Nondestructive Examination*, ANSI/AWS A2.4-98, Paragraph 18.3, p. 92.

Figure 8.41—Symbols Indicating the Nondestructive Examination of Specific Areas: (A) Plane Areas; (B) Area of Revolution—One Side; and (C) Area of Revolution—Both Sides

examination for a distance of 3 in. from the flange face. The lower symbol indicates that an area of revolution is to be examined radiographically. The width of the area is specified using the dimension line.

The symbol used in Figure 8.41(C) indicates that a pipe or tube is to be subjected to an internal proof examination and an external electromagnetic examination. As no limiting dimensions are shown, it is understood that the entire length is to be inspected.

Acoustic emission examination is typically performed on all or a large portion of a component, such as a pressure vessel or a pipe. Thus, the symbol shown in Figure 8.42 is used to indicate the application of this method of examination, which needs no specific reference to the location of the sensors.



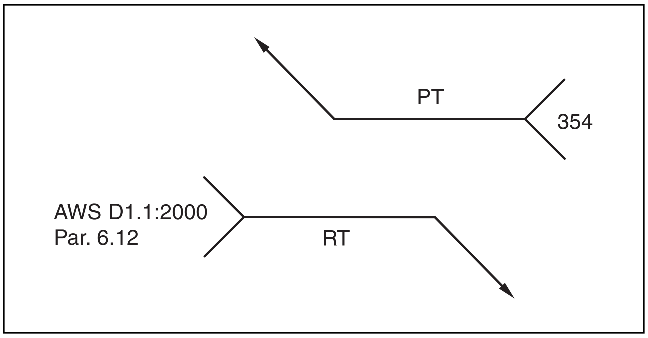
Source: Adapted from AWS Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing and Nondestructive Examination*, ANSI/AWS A2.4-98, Paragraph 18.3.3, p. 92.

Figure 8.42—Specification of Area to Be Inspected Using Acoustic Emission Testing

Specifications, Codes, and Other References

When a specification, code, or other reference is designated in a nondestructive examination symbol, the relevant information is placed in the tail. The edition of the code or standard is also included in the tail.

This convention is illustrated in Figure 8.43. In the symbol on the left, Paragraph 6.12 of *Structural Welding Code—Steel,* AWS D1.1:2000[10] is referenced. This provides acceptance criteria for radiographic examination. In the symbol on the right, The use of penetrant examination on the other side of the weldment is required; the Reference "354," which could refer to a procedure, a specification, or a drawing, provides additional information applicable to the examination. Specifications, codes, or other references need not be included in nondestructive examination symbols if they are listed elsewhere such as in drawing notes.



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 17, p. 91.

Figure 8.43—Symbols Indicating Specification, Codes, and Other References

Supplementary Symbols

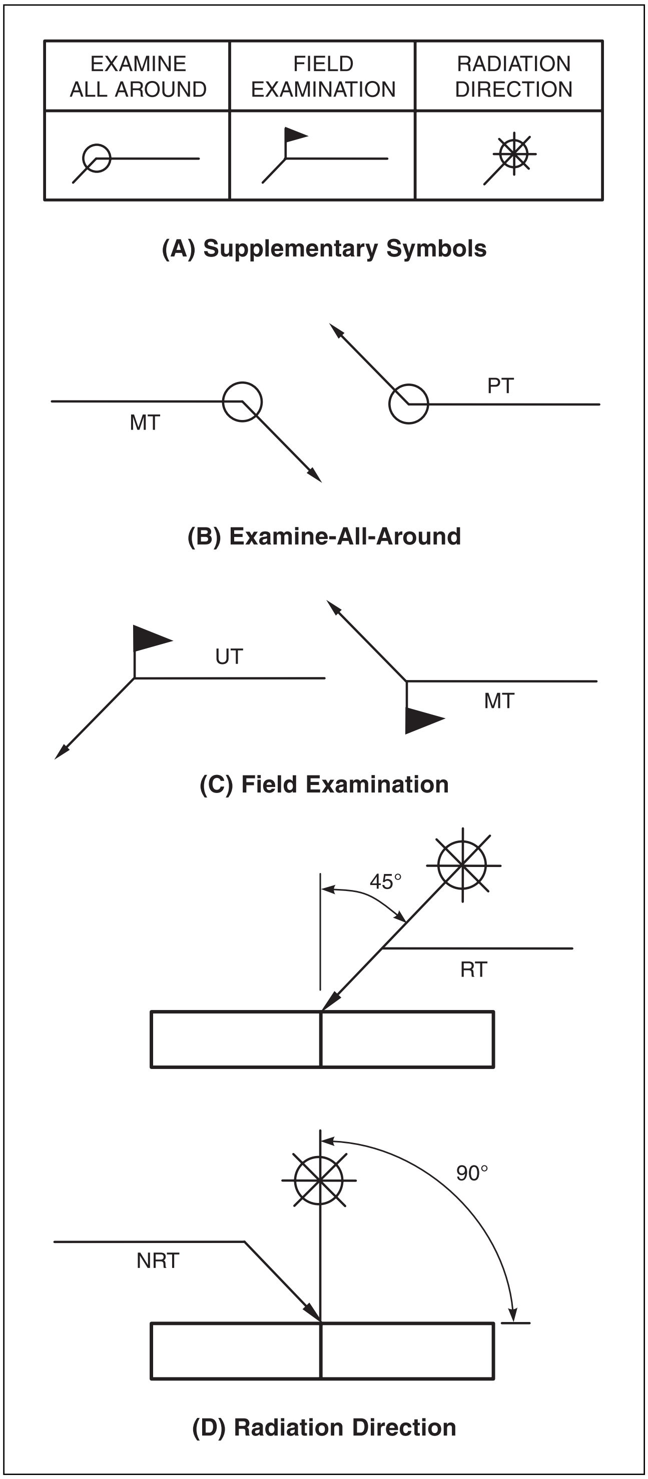
Three types of supplementary symbols are used with nondestructive examination symbols. These, the examine-all-around symbol, the field examination symbol, and the radiation direction symbol, are shown in Figure 8.44(A). Figures 8.44(B), (C), and (D) illustrate the application of these supplementary symbols.

Examine-All-Around Symbol. The examine-all-around symbol specifies that examination is to be conducted all around the weld, joint, or weldment. Examples are presented in Figure 8.44(B).

Field Examination. The field examination symbol requires that the examination be conducted in the field as opposed to in a shop or at the place of initial construction. Examples are shown in 8.44(C).

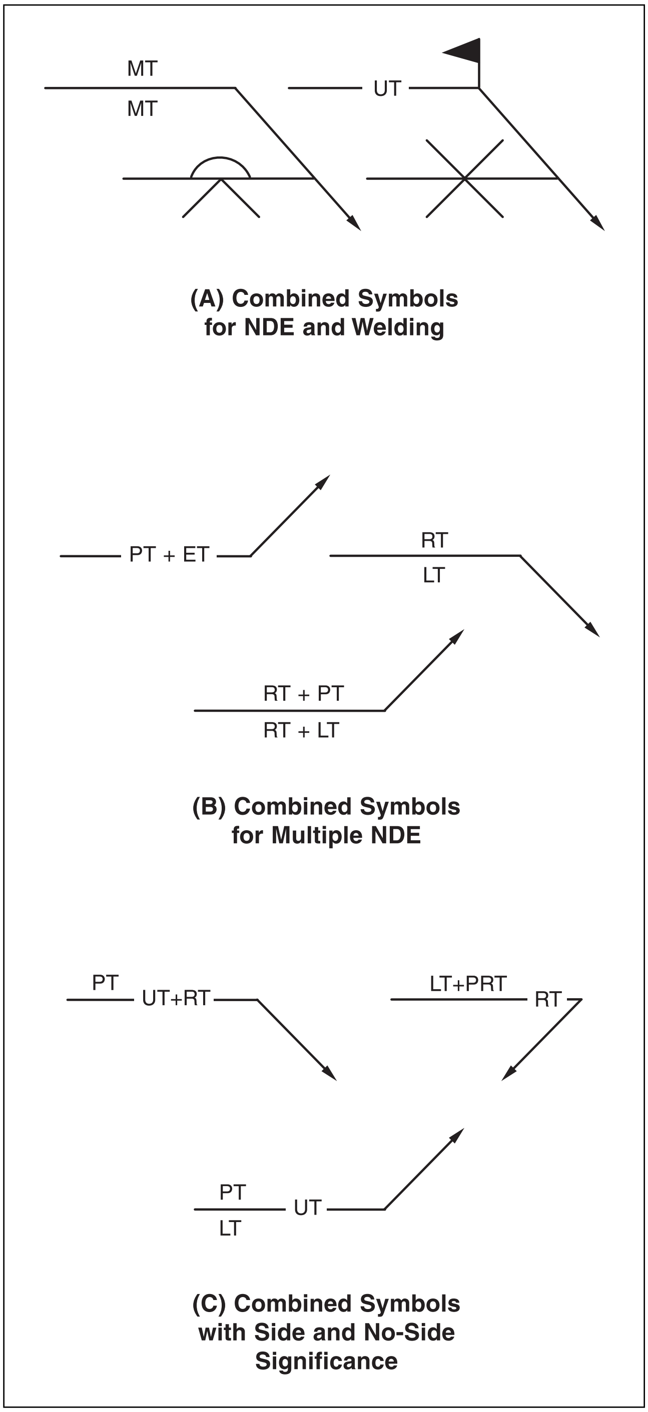
Direction of Radiation. The direction of radiation to be used in radiographic testing may be shown in conjunction with radiographic (RT) and neutron radiographic (NRT) examination symbols. The direction of radiation is indicated with a symbol that resembles a star representing the source of radiation and a line located in the drawing at the desired angle. The angle is specified in degrees. Figure 8.44(D) illustrates the use of this symbol.

10. American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraphs 14.2, 16.1, 16.2, and 16.3, pp. 89, 91.

Figure 8.44—Supplementary Symbols for Nondestructive Examination



Source: Adapted from American Welding Society (AWS) Committee on Definitions and Symbols, 1998, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4-98, Miami: American Welding Society, Paragraph 15.2, p. 90.

Figure 8.45—Combinations of Symbols: (A) Nondestructive Examination and Welding; (B) Multiple Nondestructive Examination Methods; and (C) Symbols with Side and No-Side Significance

Combinations of Welding and Nondestructive Examination Symbols

Nondestructive examination symbols can be used in combination with welding symbols in the engineering drawings. In addition, nondestructive examination symbols are often combined with each other to prescribe examination using more than one inspection method. Typical combinations of symbols are depicted in Figure 8.45.

The combination of welding symbols with nondestructive examination symbols is illustrated in Figure 8.45(A). The symbol on the left requires that a single-V-groove weld be produced first from the arrow side of the joint. Then, a back weld is to be applied from the other side of the joint. The completed weld is to be examined from each side using the magnetic particle examination method. The symbol on the right calls for a double-V-groove weld, followed by ultrasonic examination in the field from one side or the other of the joint.

The application of more than one inspection method is specified for the same workpiece by positioning the letter designations of the desired inspection methods in the appropriate position with respect to the reference line. A plus sign (+) is used to separate the designated nondestructive examination methods. This convention is illustrated in Figure 8.45(B). When an examination method with no arrow-side or other-side significance and another method that has side significance are to be used, the nondestructive examination symbols may be combined, as shown in Figure 8.45(C).

CONCLUSION

The use of welding, brazing, soldering, and nondestructive examination symbols saves time and space on drawings. The symbols and the standardized conventions for their use help minimize the repetition of the information and provide information that would otherwise be provided in copious notes or a multiple of drawing details. The reader is encouraged to become familiar with these symbols and their use in order to benefit from the economy that they afford.

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11. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

CHAPTER 9

WELDMENT TOOLING AND POSITIONING

Prepared by the Welding Handbook Chapter Committee on Weldment Tooling and Positioning:

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CHAPTER 9

WELDMENT TOOLING AND POSITIONING

INTRODUCTION

One requirement common to all forms of welding is the need to position and hold workpieces accurately. Welding fixtures are typically the most common devices used to align and retain parts for welding. Nearly all welding fixtures are designed and built to suit the specific requirements of a single assembly. For this reason, most welding fixtures are quite expensive and often only justified when fabricating many units.

When a limited number of fabricated units are needed for a very small batch or prototype work, other methods of positioning and holding workpieces are usually employed. For example, they may be positioned and held manually or fixtured with any arrangement of C-clamps, bar clamps, magnets, or framing squares on cast iron platens. Temporary fixturing may be used, time and economics permitting. Regardless of the quantity involved, each weldment must be properly fixtured to ensure that it is constructed correctly.

This chapter is intended to serve as a guide with respect to the selection of appropriate tooling and positioning devices, providing suggestions to facilitate improved fixturing applications. The challenge involves the selection of the method of fixturing best suited for the application in terms of cost and fitness for purpose. These criteria vary widely from application to application as they relate to the various fixturing and positioning selections.

FIXTURES

In welding engineering, the terms *fixture, jig,* and *tooling* have essentially the same meaning. The function of a fixture is to facilitate a positional relationship between the workpieces themselves or between the workpieces and a tool during the assembly of a weldment. The use of fixtures promotes good fit-up tolerances, resulting in consistently high-quality weldments produced at a higher rate of productivity with less distortion and at lower costs. Weldments can be joined either partially or completely in the fixture. If the assembly is tack welded together and removed prior to welding, the device used is typically called a *tacking* or *fitting fixture*.

Fixtures serve three major purposes. They are used as tacking fixtures, welding fixtures, and holding fixtures. The benefits of fixturing include the following:

1. Minimized decision making and measurements required of the operator with respect to the location and orientation of the weldment,
2. Improved identification of workpieces that are out of tolerance,
3. Enhanced fitup of workpieces to achieve tighter tolerances,
4. Minimized weld distortion,
5. Less manufacturing labor needed to produce the weldment,
6. Improved weld consistency and quality, and
7. Fewer product errors as a result of appropriate fixture identification.

Fixtures and positioners enhance the execution of manual, semi-automatic, and fully automated welding processes by maximizing the orientation of the weld joint to permit welding in the flat position. Depending on the complexity of their design, fixtures can be expensive to build. Nonetheless, they are cost effective due to the higher productivity and improved weld quality that result from their use.

The design and manufacture of fixtures should reflect the number of weldments to be produced. Small quantities may be produced on temporary fixtures assembled specifically for the product being manufactured. For large quantities, fixtures often form an integral part of the production system. They may include devices that render automatic clamping or mounting to a positioner and accommodate welding by an automated welding machine or an industrial robot.

Several standard fixturing components, which include light- and heavy-duty clamping devices, are available commercially. These devices can be incorporated into dedicated fixtures for large production runs or into adjustable or modular fixtures that can be easily modified for short-run products. For the most part, fixturing may be purchased from positioning and fixturing system integrators, tool and die shops, and machine shops. Alternatively, they can be designed and built by plant operations personnel to facilitate the production of one or more assemblies.

Basic Design Requirements

Fixture designs should incorporate numerous desirable features. Ideally, fixtures should be simple and inexpensive as well as capable of producing a weldment that requires a minimum of machining while controlling essential workpiece dimensions and tolerances. Weld joints should be accessible through holes, slots, or cutouts in the fixture with the best possible fitup for welding in the flat position whenever possible.

In addition, production fixtures are typically designed to be more rigid than the weldments undergoing fabrication. Point-of-contact tooling components should be made of tool steel or Class III copper. They should be doweled or keyed to ensure accuracy and ease of replacement.

During welding, hold-downs, clamps, pneumatic control devices, and the threads of bolts and nuts should be protected from weld spatter. Compressed air cylinders used for clamping should clamp in the retracted position to shield the cylinder rod from weld spatter. Pneumatic piping should consist of rigid pipe or fire-retardant hose with protection against spatter entrapment. As counterbored mounting bolt heads tend to fill with spatter, protruding mounting bolts, which can be gripped for easy removal, are preferred.

Fixture designs should allow for the assembly of the workpieces with a minimum number of temporary welds visible upon completion of the weldment. They must also facilitate the location of the workpieces during assembly, provide flexibility of adjustment during welding, and ensure easy removal of the workpiece from the fixture once welding has been completed. To account for thermal reactions, designs should make use of materials that prevent deflection or failure. Precamber or thermally conductive backup strips, used for distortion control, should provide freedom of movement in one direction to compensate for shrinkage and the angular movement of the components as the weldment cools in the fixture.[1]

With respect to electrical conductivity, the work-lead connection point and the selection of clamps and materials used in the fixture are important considerations for effective grounding and the elimination of unstable arc conditions. Designs should allow for preheat, cooling, or inert gas backing of welds, when required. Depending on the degree of sophistication required, workpiece presence detection, system feedback, and control interlocks may be considered in the fixture design.

The designer must decide how many welds are to be executed while the workpiece is in the fixture. For example, the back side of a full-penetration weld may be deposited after the weldment is removed from the fixture. Sufficient welds should be completed in the fixture to restrain the assembly from distortion during the completion of welding outside the fixture. Since most weldments are fabricated as subassemblies, tolerances are critical. However, the intermediate dimensions are often less important than the end and edge dimensions, which control the fit in the final assembly.

The following procedures should be followed sequentially in the elaboration of fixture designs:

1. Review all pertinent workpiece manufacturing and engineering data—concentrating on form, fit, and function aspects of the product—and develop tentative design concepts;
2. Consider all pertinent operations criteria—including heat transfer and grounding capabilities, part loading direction and accessibility, part flow and staging, and wear maintenance—and develop tentative design concepts;
3. Survey all pertinent process data—including welding processes, weld accessibility and orientation, grounding, magnetic properties, and inspection—and develop tentative concepts;
4. Review all pertinent operator criteria—including ergonomic issues, safety, and part-handling considerations—and develop tentative design concepts; and
5. Evaluate the selected tentative designs to identify the most economical fixturing per part, taking into account design, fabrication, operation, amortization, and any other applicable costs.

With respect to safety considerations, fixture designs should provide the operators, workpieces, fixtures, and tools a safe, ergonomic work environment before, during, and after the work cycle.

1. For additional information on the control of shrinkage and distortion, the reader is encouraged to consult Chapter 5 of this volume as well as Blodgett, O. W., 1976, *Design of Weldments,* Cleveland: The James F. Lincoln Arc Welding Foundation.

Clamping and Holding Systems

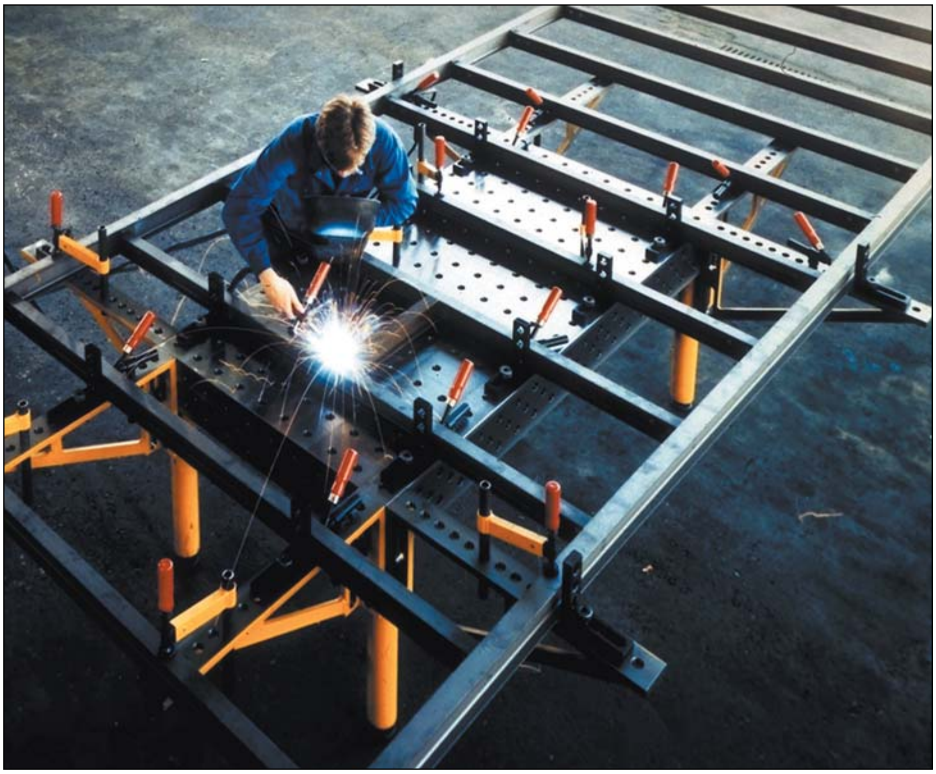
Clamping devices must not only apply and maintain sufficient holding force on the workpiece but also counteract thermal and tooling forces. Proper clamp design is determined by making a thorough analysis of the workpiece and the forces that act upon it. Good clamp design can reduce process and product costs by increasing quality and productivity. A wide range of clamping devices can be integrated into welding fixtures. These include screws; straps; cams; toggles; and hydraulic, pneumatic, magnetic, and vacuum devices.

The following factors should be taken into consideration when selecting a clamping device:

1. Clamping pressure should act on the workpiece to provide support without distortion and prevent excessive deflection or failure;
2. The workpiece should be held in the proper orientation and location, allowing for predictable thermal changes in the properties of the weldment;
3. Loading and unloading should be relatively quick and easy to perform without binding;
4. Safe operation should be assured throughout the work cycle;
5. Good electrical conductivity should be guaranteed;
6. Heat dissipation or retention should be provided for, as required;
7. Large, long handles and knobs should be available to facilitate manual operation with gloves; and
8. The device should perform as an integral part of the fixture without interference.

Modular Tooling

The use of platens and modular tooling allows increased flexibility by providing interchangeable, cost-effective fixturing. Figure 9.1 depicts a typical modular fixturing application for the fabrication of a machine support frame. This product provides an accurate, stable work surface with precision hole patterns for a multitude of hold-down, locating, bracing, and clamping components. As modular tooling can be disassembled, it requires much less storage space than conventional fixturing.



Photograph courtesy of Bluco Corporation

Figure 9.1—Modular Tooling

Figure 9.2 demonstrates typical variations of modular tooling that can be used to fixture virtually any weldment. This versatility comes in handy for custom work, prototypes, and varied production run requirements.

APPLICATIONS

Although many types and variations of fixtures are utilized in metal fabrication, most fall into three broad categories. These categories are tacking fixtures, welding fixtures, and holding fixtures.

Tacking Fixtures

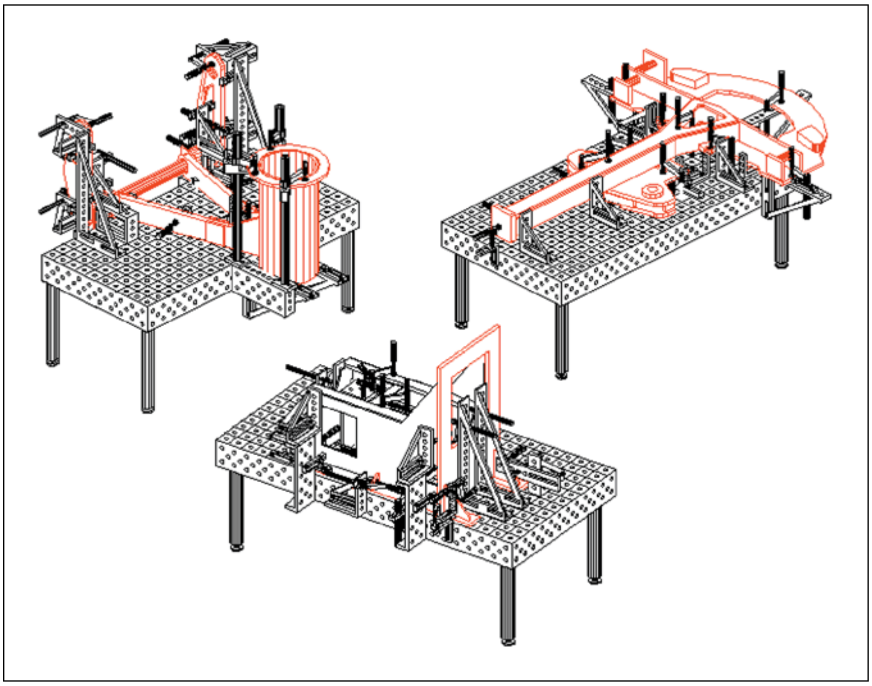
Tacking fixtures are used to locate the component parts of a weldment in their proper orientation with the proper fitup for tack welding. The weldment is removed after tacking, and finish welding is performed in another operation or fixture. Tacking fixture construction may be simple as these fixtures do not typically need to withstand the heat stress consistent with welding fixtures. Figures 9.3(A) and (B) present a tacking fixture in the unloaded and loaded conditions, respectively.

Welding Fixtures

Welding fixtures are used to hold component parts of the weldment in the proper orientation with the proper fitup while welding is performed on the weldment. These fixtures essentially eliminate additional handling. They are constructed to withstand the thermal stress and pressure of the weldment during the welding process. Seamers, precision fixtures, and some robotic welding fixtures fit into this category.

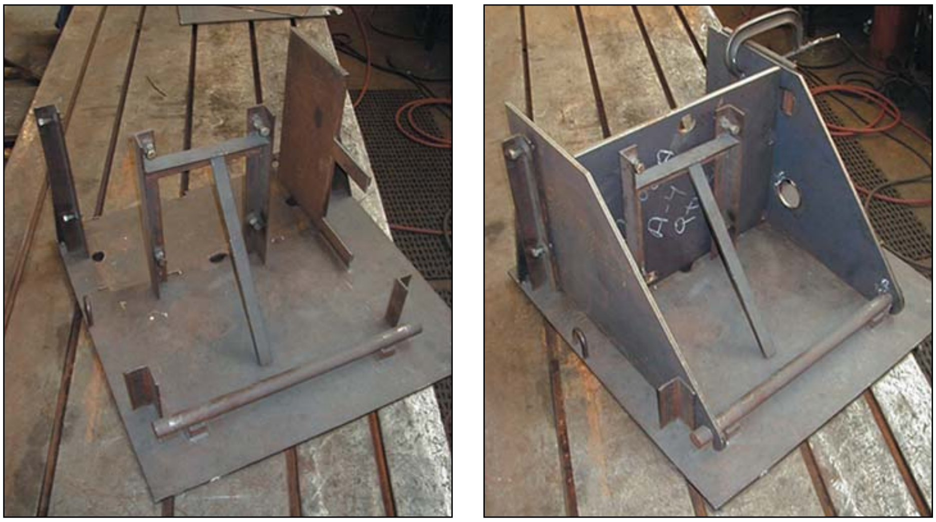
Seamers are designed for straight-line weld fixturing for welding performed in the flat or vertical position. Figure 9.4 presents an external seam welder. Dual banks of clamping fingers hold down the opposing workpiece components against a suitable backup for consistent quality butt welding.

Figure 9.5(A) depicts a typical internal flat-sheet clamping arrangement for the welding of internal cylindrical longitudinal seam welds and flat sheets. Figure 9.5(B) presents a cross section of an external flat-sheet clamping arrangement typically used for external cylindrical longitudinal seam welds. A mandrel and a backup bar serve as support and heat sink at the weld joint clamping area. Interchangeable mandrels can be utilized to weld flat sheets, cylinders, cones, angles, and open-end box configurations. Preheat, cooling, flux, and inert



Courtesy of Bluco Corporation

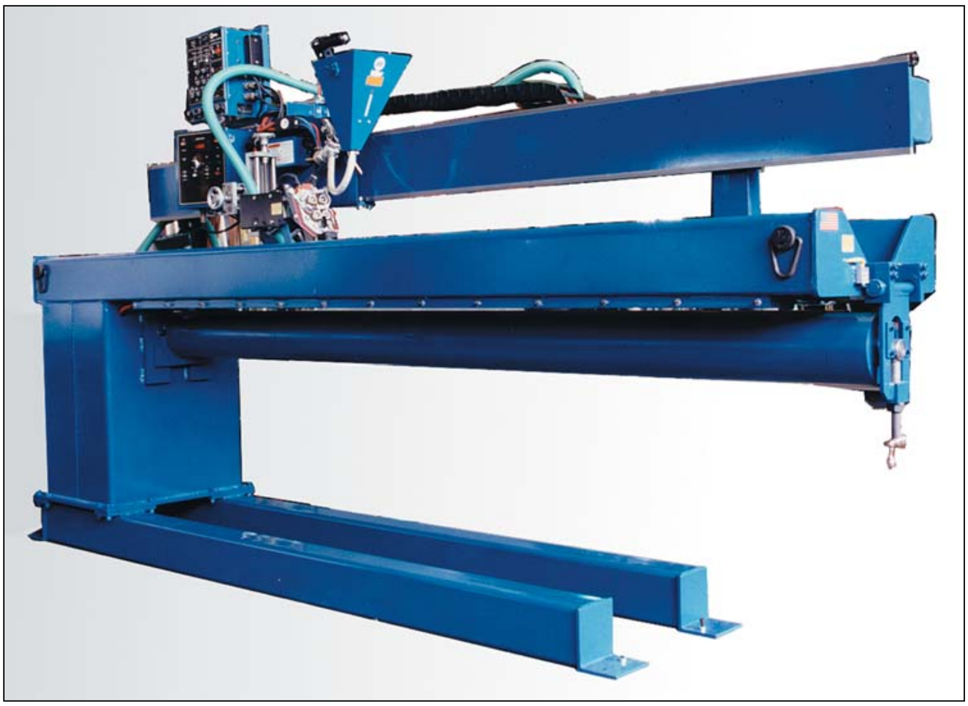
Figure 9.2—Modular Tooling Variations



Photographs courtesy of Pandjiris, Incorporated

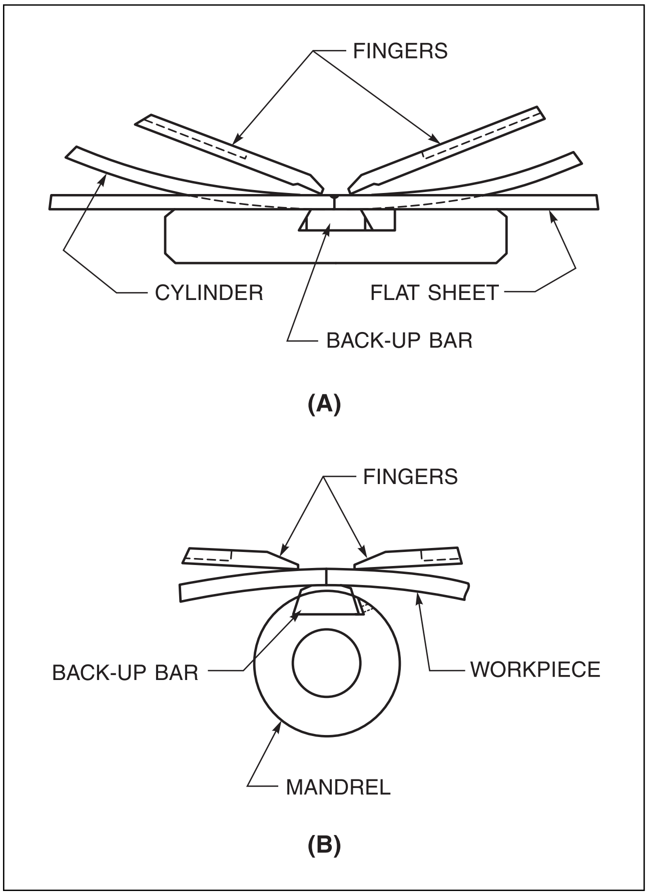
(A) (B)

Figure 9.3—Tacking Fixture: (A) Unloaded and (B) Loaded



Photograph courtesy of Pandjiris, Incorporated

Figure 9.4—Seam Welding Fixture



Courtesy of Pandjiris, Incorporated

Figure 9.5—Cross Sections of Seamer Clamping Configurations: (A) Flat-Sheet, Internal and (B) External

gas can be used in the backup or mandrel for improved weld quality. This type of fixture is designed to facilitate welds executed with up to 100% penetration with a minimum of distortion.

Precision welding fixtures are designed and used to produce a fabrication to close tolerances. Typical precision fixtures are shown in Figures 9.6, 9.7, and 9.8. Figure 9.6 shows the right-end subassembly that is one of the detailed parts of the aluminum enhanced launcher electronic system (ELES) weld assembly for the Patriot Advanced Capability Missile Program (PAC 3). This ELES welded assembly will house all the electronics required for the missile to communicate with the launcher. In addition to this precise fixture, detailed, step-by-step assembly and welding procedures along with several welding procedure specifications (WPS) were required to meet the fabrication tolerances of 0.030 in. (0.762 mm).

Figure 9.7 presents a two-piece fixture arrangement used to weld an oxygen sensor fitting into a catalytic converter body stamping. The oxygen sensor is located on the centerline of the machine spindles. The fixture and tooling rotate 360° while the torch is manipulated by cams to track the weld joint.

A three-piece fixture arrangement for the simultaneous welding of inlet and outlet pipes to a catalytic converter body is shown in Figure 9.8. The catalytic converter body fixture is mounted in a center clamshell cradle that hinges open to facilitate the loading and unloading of workpieces. The center cradle is mechanically synchronized with the outboard spindles. The three loose components are rotated 360° for welding. As the inlet and outlet of the catalytic converter are offset, cam-controlled torch motion is required to track the weld joint.

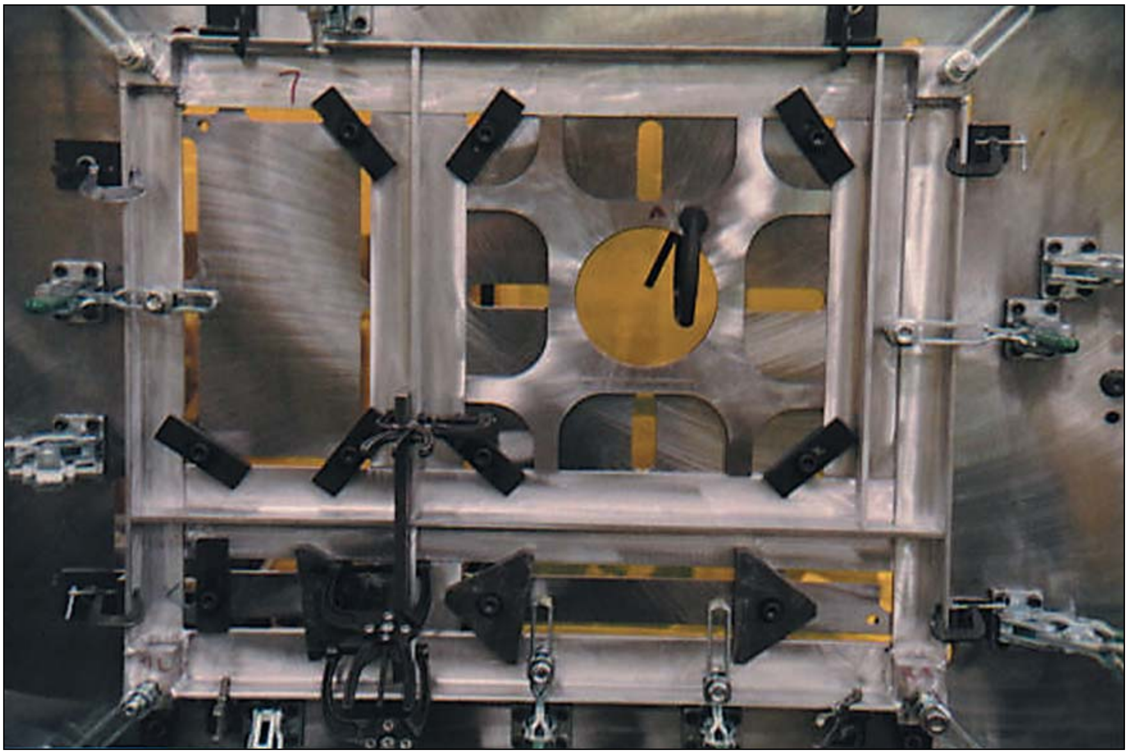
Robotic welding fixtures must allow the robot unobstructed access to the workpiece. Therefore, these fixtures must have low-profile clamps that are located away from the weld seam. They have at least two reference points that are in a fixed relationship to the weld seams of the workpiece. The robot is then programmed to locate the reference points on the fixture. The reference points establish a coordinate system, which the robot uses to find its way along the weld seams on the workpiece.

Robotic welding fixtures should be designed to permit the workpieces to be loaded and removed rapidly. The robotic cell shown in Figure 9.9 includes a turntable and a dual station headstock and tailstock configuration that allows the operator to load and remove the workpiece while the robot executes the production welds behind the partition. At the completion of the cycle, the turntable rotates 180°, and the process is repeated.

Welding fixtures for intricate, complex, or bulky weldments should be reviewed to determine the feasibility and practicality of building a fixture to complete the welding in a single stage. In many cases, several types of fixtures are used to complete a weldment. For example, components of the weldment may be tack welded in a tacking fixture or subassembly fabricated in a welding fixture and then transferred to a holding fixture, typically a positioner, to process the weldment in a series of manageable subassemblies.

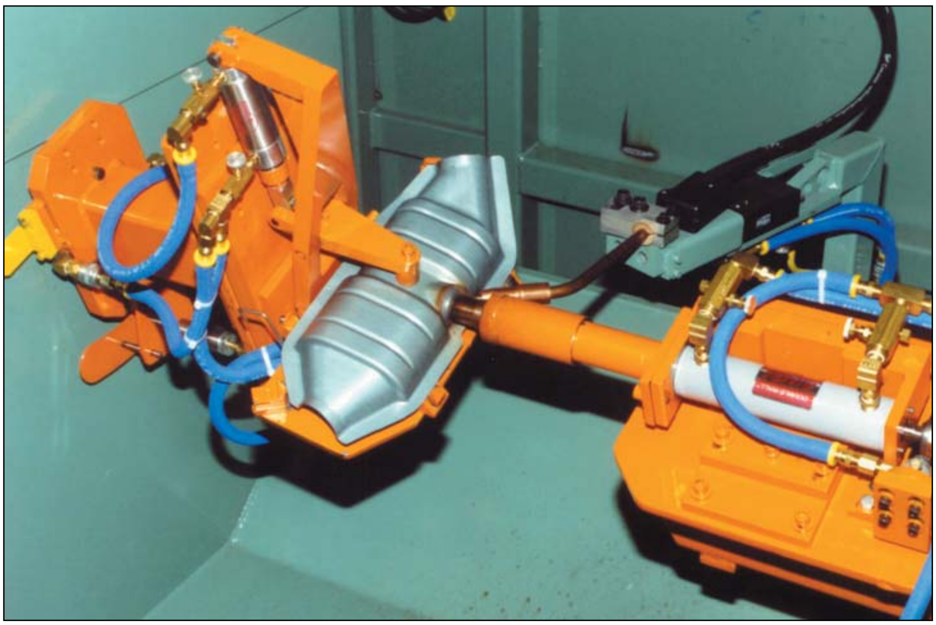
Holding Fixtures

Holding fixtures are designed to maintain previously tacked components or subassemblies in the proper orientation on a positioner. These fixtures may have a positioning device integral to their design to achieve the proper welding orientation of the weldment. Like



Photograph courtesy of Lockheed Martin Missiles and Fire Control-Dallas

Figure 9.6—Welding Fixture for the Patriot Advanced Capability (PAC 3) Missile Enhanced Launcher Electronic System (ELES) Weld Assembly



Photograph courtesy of Melton Machine and Control Company

Figure 9.7—Two-Piece Welding Fixture

Photograph courtesy of Melton Machine and Control Company

Figure 9.8—Three-Piece Welding Fixture

Photograph courtesy of ABB Flexible Automation, Welding Systems Division

Figure 9.9—Operator Loads an Assembly onto a Fixture in a Robotic Welding Station

welding fixtures, holding fixtures are constructed to withstand the thermal stress and pressure the weldment undergoes during the welding process. In Figure 9.14, a crawler frame is held in place on the drop-center frame in a holding fixture.

POSITIONERS

Positioners are mechanical devices that support and move the weldment to the desired position for welding and allied operations. The positioner often moves the weldment as welding progresses along a joint. Fixtures may be mounted on the positioners to place the fixture and the weldment in the most advantageous positions for loading, welding, and unloading.

In some cases, the joints of an assembly are first tack welded in a tacking fixture to hold the assembly together. The weldment is then removed from the fixture and mounted on the positioner to weld the joints in the best position for economical production. Weldments on a positioner can be repositioned during and upon completion of the welding and for the cleaning, machining, and nondestructive inspection of the weld.

The positioner and the load must work together as a balanced entity to facilitate the stable and uniform movements of the positioner as required by the welding operation. A capacity rating is calculated for the positioner to reflect this balance. This rating is based on the total load, which consists of the combined weight of the workpiece and the fixturing, and the location of the center of gravity (CG) of the combined load. The center of gravity of a body is the point at which the body would be perfectly balanced in all positions if it were suspended at that location.

Two dimensions are used to locate the center of gravity of the combined load: (1) the distance from the surface of the positioner table to the center of gravity of the combined load and (2) the distance from the axis of rotation to the center of gravity of the combined load, referred to as *eccentricity*. Thus, it is common practice to rate a positioner for a given combined load at a given center of gravity and eccentricity.

The combined load that can be mounted on a positioner decreases per the rated torque capacity as the center of gravity of the workpiece moves away from the tilt and rotation axis (see the section titled "Technical Considerations"). In conventional positioners, the surface of the table is not on the tilt axis but offset by a distance referred to as the *inherent overhang*. This distance varies depending on the size of the positioner.

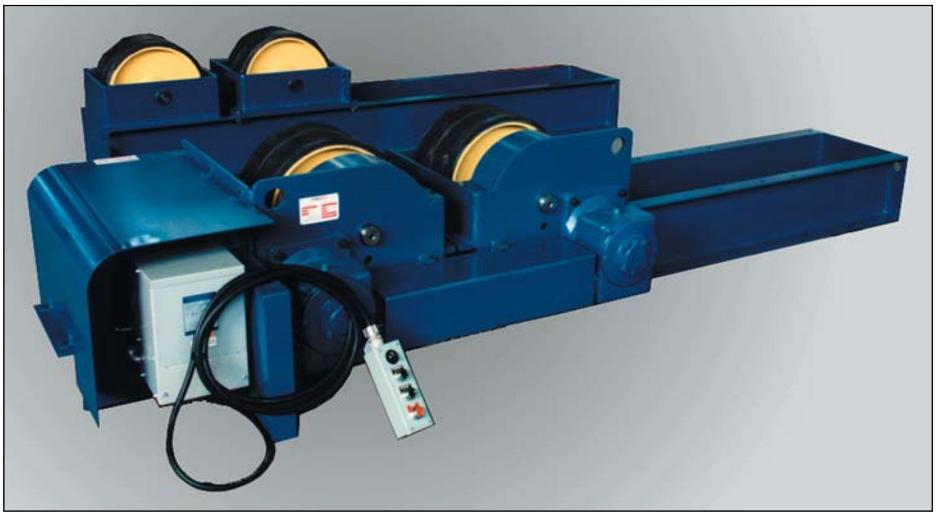
TYPES OF WELDMENT POSITIONING AND POSITIONERS

Positioning can be done using three different types of motion. One-motion positioning involves rotation about one axis. This is normally accomplished with turning rolls, headstock and tailstock arrangements, or turntables, all of which rotate the assembly about a single axis. Two-motion positioning is a combination of rotation and tilting. This is accomplished with a positioner that has a tilting table as well as a turntable. Three-motion positioning is achieved by adding vertical movement with an elevating device in the machine base, thus providing rotation, tilt, and elevation.

Turning Rolls

Turning rolls are used in sets, as shown in Figure 9.10. Each set consists of one powered roll and one or more idler rolls, each roll having two or more wheels. Turning roll design is quite simple. A set of rolls normally consists of a fabricated steel frame, wheels, a drive train, a drive motor, and controls. Several different wheel-drive designs are available, including those that utilize friction, gears, and chains. Simplicity of design results in low initial costs as well as low maintenance and repair costs. Standard models can be used for many applications.

Turning rolls can also be manufactured according to specific requirements, with variations in wheel construction, surface composition, weldment weight capacity and diameter, fitup and alignment, special motions, and unitized frames. Features and accessories include modified wheel materials, modified wheel spacing, overload discs, antiskewing mechanisms, and digital tachometers for the measurement of surface speed in inches per minute [in./min] (centimeters per minute [cm/min]).



Photograph courtesy of Pandjiris, Incorporated

Figure 9.10—Turning Rolls

Applications. Turning rolls are normally used to achieve the rotation of a cylindrically shaped weldment about its horizontal axis. They range in capacity from 500 pounds (lb) (200 kilograms [kg]) to more than 2500 tons (1136 M tons). Noncylindrical assemblies can be rotated on turning rolls using special round fixturing to hold the assembly, in which case the fixture rests on the turning rolls.

Cylindrical sections may be aligned for tacking with fit-up rolls, which are idler rolls that have adjustable wheel assemblies for raising or lowering the sections into position. Fit-up rolls facilitate the up-and-down and side-to-side movement needed to orient the ends of the cylinder into position for welding.

When selecting the proper capacity for turning rolls, consideration must be given to the tractive effort needed to rotate the workpiece (see the section titled "Technical Considerations"). Turning rolls may be located on powered or idler travel cars for longitudinal transport of the workpiece. Travel cars can save several material-handling lifts of a vessel during the fabrication, nondestructive examination, painting, sandblasting, or final assembly processes, for example.

Turning rolls can position seams for manual, semiautomatic, and automated welding in the flat position. With automated welding, circumferential welds may be rotated under a fixed welding head. Longitudinal welds can be made with a welding head mounted on a traveling carriage or manipulator.[2]

Stability. Stability should always be a matter of concern when using turning rolls. The workpiece and rolls should be inspected prior to each operation for clear, unobstructed rotation and closely surveyed for any protrusion or interference. The weight of the workpiece should also be monitored, as an individual turning roll can be overloaded by a workpiece if the longitudinal weight distribution is neglected. Turning rolls are susceptible to instabilities such as overturning, creep, drag, and overload. Even the most precise applications suffer from one or more of these instabilities, which are discussed in more detail below.

An eccentric load or unbalanced weight that places the center of gravity outside the turning roll's tire contact area typically causes the workpiece to overturn horizontally or longitudinally. Eccentric loads or unbalanced weights may result from the addition of external or internal attachments as well as the removal of materials such as ports or manholes from the workpiece (see the section titled "Technical Considerations"). This condition results in the workpiece's rolling off or tipping out of the turning rolls.

2. For additional information on carriages, see Chapter 11, "Mechanized, Automated, and Robotic Welding."

Although creep—the translation or motion of the workpiece in either direction along the centerline of the workpiece during rotation—is the most prevalent type of instability, it is the most elusive to predict and resolve. Creep is typically caused by turning-roll mismatch, installation placement and alignment inconsistencies, or workpiece-related imperfections. Some causes for this phenomenon include mismatch of the power and idler rolls' centerline and side-to-side height, worn tires or turning roll wheels that are out of perpendicular, and a slight taper in the diameter of the workpiece. Creep is virtually impossible to eliminate, making it important to monitor the orientation of the workpiece on the rolls periodically during operation.

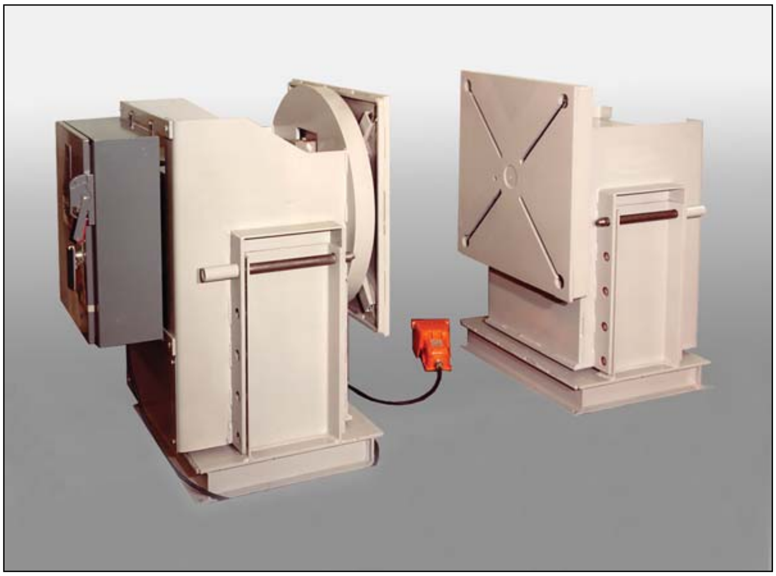
Another type of instability, known as *drag*, exists when nonparallel or out-of-square turning roll centerlines generate large opposing drag forces between the power and idler rolls and the workpiece. Another, termed *overloading*, occurs when a workpiece's eccentric load exceeds the machine's rated capacity. This condition can cause defective welds as a result of rotation overdriving or stalling, component failure, or equipment damage. Overloading can be induced by improper wheel-center distance spacing, improper weight distribution, or excessive eccentricity.

Headstock and Tailstock Positioners

A headstock is a single-axis positioning device that provides the complete rotation of a vertical table about the horizontal axis. This device provides easy access to all sides of a large weldment so that the work can be performed in the flat position. A headstock may be used independently to rotate weldments about the horizontal axis if the overhanging load capacity is not exceeded. The welding of elbows or flanges to short pipe sections serves as an example of this application.

A headstock is sometimes used in conjunction with a tailstock, as shown in Figure 9.11. The tailstock usually has the same configuration as the headstock, but it is not powered. Alternatively, a simple trunnion, an outboard roller support, idler roll, or any other free-wheeling support structure that is best suited to the configuration of the weldment may be used in place of a tailstock. In all instances, the precise installation and alignment of the headstock and tailstock positioners are essential so that the axes of rotation are aligned. Otherwise, the equipment or the weldment may become damaged.

The concept and application of headstock and tailstock positioners are much the same as those of the lathes used in machine-shop operations. However, in welding fabrication, the applications can be more versatile with the use of special fixtures and the addition of horizontal or vertical movement, or both, to the bases of the headstock and tailstock.



Photograph courtesy of Pandjiris, Incorporated

Figure 9.11—Headstock (Left) and Tailstock (Right) Positioners

Applications. Headstock and tailstock positioners are well suited for the handling of large assemblies that are to be welded. Typical assemblies are structural girders, truck and machinery frames, truck and railroad tanks and bodies, armored tank hulls, the components of earth-moving and farm equipment, turbine parts, pipe fabrication, and large transformer tanks. These positioners are sometimes used in conjunction with one or more welding head manipulators or with other automated welding equipment. Appropriate holding fixtures and tooling are needed with headstock and tailstock positioners to ensure the safe mounting of the workpiece to the faceplate of the table.

Sound engineering principles and common sense must be applied in the joining of an assembly held in a headstock-tailstock positioning fixture. Most long, narrow weldments that are supported at the ends tend to sag under their own weight or distort slightly as a result of fabrication. The rigid mounting of a weldment between the two positioner tables is to be avoided when the headstock and tailstock are installed in fixed locations. Otherwise, the distortion caused by welding may damage the equipment when the weldment is rotated. A flexible connection must also be provided at each end of a clamping and holding fixture designed to accommodate a weldment between the headstock and tailstock tables. A universal joint or pivot trunnion in the fixture is recommended to compensate for a lack of tolerance in the weldment components.

When selecting the proper capacity for the headstock, consideration must be given to the inertia of a large rotating weldment. The larger the polar moment of inertia, the greater is the torque required to start and stop rotation.[3] When one or more components of a weldment are at a considerable distance from the rotational axis, the flywheel effect created by this condition can cause serious damage to the headstock drive and gear train. Under these circumstances, rotation speed should be low to avoid excessive starting, stopping, and jogging of the torque loads. When usage involves weldments with a significant portion of the mass located at some distance from the rotation centerline, it is advisable to select a headstock capacity greater than that normally needed for symmetrical weldments of the same mass.

Features and Accessories. Many features and accessories can be added to headstock and tailstock

3. The unbalanced torque required to accelerate or decelerate a rotating body is related to the polar moment of inertia of the body and the angular acceleration by the following equation:

$$To = J_M \alpha$$

where To = unbalanced torque, lb-in. (N × m); J_M = polar moment of inertia of the mass about the axis of rotation, lb-in.-second^2 (N × m-second^2; and α = acceleration or deceleration, revolutions per minute squared (rpm^2) (radian per second squared [rad/s^2]).

positioners to provide versatility. Some common accessories used with this equipment include the following:

1. Constant- or variable-speed drives,
2. Self-centering chucks or grippers,
3. Automatic indexing controls,
4. Powered elevation,
5. Power and idler travel carriages with track and locking devices,
6. Through-hole tables,
7. Powered tailstock movement to accommodate varying weldment lengths and facilitate clamping, and
8. Digital tachometers for the measurement of revolutions per minute (rpm) or surface speed (in./min [cm/min]).

Turntable Positioners

A turntable is a single-axis positioning device that rotates a horizontal table or platform about a vertical axis, thus allowing rotation of a workpiece about that axis. Turntables range in size from small bench units to large floor models. A typical turntable is shown in Figure 9.12.

Applications. Turntable positioners are available in capacities from 50 lb (20 kg) to over 500 tons (227 M tons). They are used extensively for automated welding, scarfing and cutting, cladding, grinding, polishing, assembly, and nondestructive testing. Turntables can be built using the lazy-susan concept to index several assemblies on a common table. In this case, several smaller turntables are mounted on the main table together with an indexing mechanism. The turntable shown in Figure 9.9 allows an operator to load and unload the work for a welding robot.

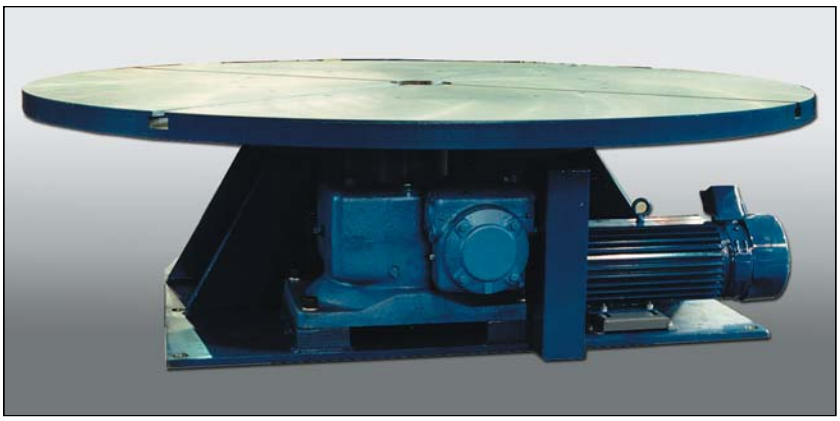
Features and Accessories. A turntable positioner can be equipped with a number of optional features and accessories. The following are some popular adaptations:

1. Constant- or variable-speed drive,
2. Manual table rotation,
3. Indexing mechanism,
4. Tilting base,
5. Self-centering chuck,
6. Travel carriage and track,
7. Through-hole in the center of the table, and
8. Digital tachometer for the measurement of rpm or surface speed (in./min [cm/min]).

Tilting-Rotating Positioners

When versatility in positioning is required for shop operations, the tilting-rotating positioner is ideal. This positioner can perform two functions. It positions the weldment so that the welds are easily accessible and the operator can work in the flat position. It also provides work travel for welding with a stationary welding head. If work travel is intended, the drive system for rotation must have variable speeds. Commonly, travel about the rotation axis is used to make circumferential welds. The tilt axis is less frequently used for work travel and is usually equipped with a constant-speed drive.

In most cases, the positioner table can be tilted through an angle of 135°, including the horizontal and vertical positions. The turntable mechanism is mounted



Photograph courtesy of Pandjiris, Incorporated

Figure 9.12—Typical Turntable Positioner

on an assembly that is pivoted in the main frame of the machine to provide a tilt axis. The tilt angle is limited by the design of the frame.

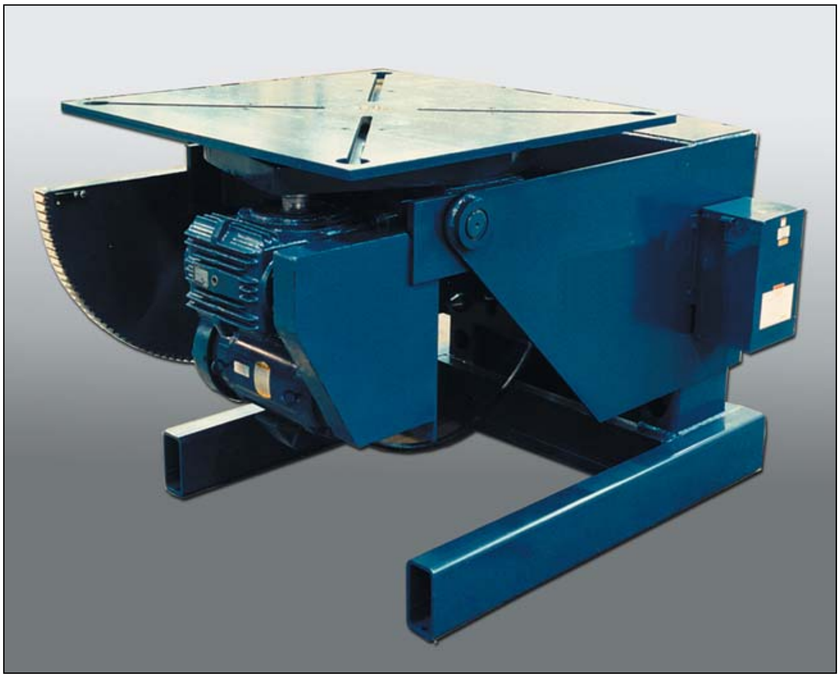
Two common gear-driven tilting positioners differ by the limitations imposed by their tilt mechanism. The flat 135° positioner can tilt the table from the horizontal position through the vertical to 45° past the vertical. A typical positioner of this type is shown in Figure 9.13. To provide clearance for the table and weldment when tilted past the vertical position, the base can be mounted on legs that enable the positioner to be raised to an appropriate height for the load to clear the floor. The other common configuration is the 45°–90° design. This positioner can tilt the table from 90° forward through the horizontal to 45° backward. The capacities of these positioners range from approximately 50 lb (20 kg) to over 4000 tons (1818 M tons). A broad overlap exists in basic capacities of the two common types of positioners. The choice depends upon the application.

Drop-Center Tilting Positioners

For special work in which it is advantageous to use a tilt drive for work travel, a tilting positioner of special design can be used. A special tilt frame fixture situated between a headstock and a tailstock is particularly useful for this application. Work travel about the fixture's tilt axis is employed, for example, in the fabrication of hemispheric pressure vessel heads from tapered sections. The welding fixture is mounted on the positioner table so that the center of a fixtured head coincides with the positioner's tilt axis. Rotation around the tilt axis must be provided to carry out the welding of the meridian seams.

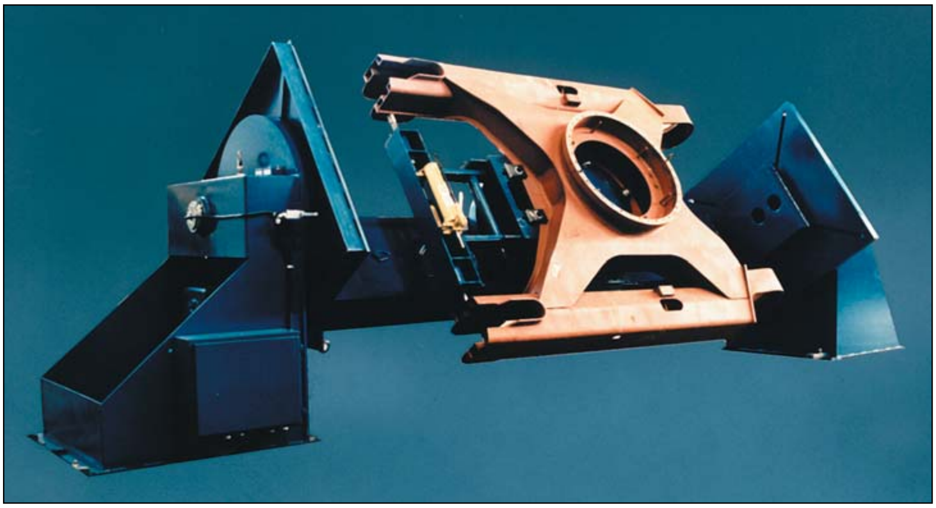
Such mountings are not typical for a weldment on a standard tilting positioner because of its inherent overhang. To avoid this difficulty, a drop-center positioner whose trunnion assembly has been modified so that the tilt axis lies in or below the plane of the table face may also be used. A hemispheric head can then be mounted so that the center is on the tilt axis. The arrangement of a crawler frame on a typical drop-center positioner is shown in Figure 9.14.

The maximum size of weldment that can be handled on a drop-center positioner is limited by the distance between the members on the vertical side of the fixture. In addition, this type of positioner requires more floor space than a conventional positioner of the same table size because the tilt journals are situated at either end of the fixture rather than beneath it.



Photograph courtesy of Pandjiris, Incorporated

Figure 9.13—Typical Flat 135° Tilting Positioner



Photograph courtesy of Pandjiris, Incorporated

Figure 9.14—Fabricated Crawler Frame on a Drop-Center Positioner

Powered-Elevation Positioners

When a positioner is intended for general-purpose application in a welding shop, a flat 135° positioner with powered elevation is generally recommended because of its greater versatility compared to the 45°–90° design. However, this type of positioner, available in capacities up to about 60 tons (27 M tons), is also the most costly. A typical powered-elevation positioner is shown in Figure 9.15.

The ability to raise the chassis of a flat 135° positioner to permit the full tilting of large weldments is particularly useful. A manually adjustable positioner must be raised and lowered with a shop crane while the positioner is unloaded. This limitation is avoided when a powered-elevation positioner is used for the application. The positioner, either loaded or unloaded, can be raised and lowered under power with integral rack-and-pinion, jackscrew, cable, or chain drives.

A powered-elevation positioner used in the fabrication of a flanged cylinder is illustrated in Figure 9.16. In Figure 9.16(A), the axis of the spool is horizontal, permitting the girth welds to be made. In Figure 9.16(B), the table is tilted upward 45° to allow the first fillet weld to be made in the optimum position. In Figure 9.16(C), the chassis is elevated, and the table is tilted downward 45° in order to make the second fillet weld.

Special Positioners

A number of variations of the basic tilting-rotating positioner are useful for specific applications. The sky-hook positioner, shown in Figure 9.17, is essentially a turntable that is mounted on the end of a long arm. The arm is attached to a headstock that provides tilting capability. This configuration provides unlimited rotation about both the tilt and the rotation axes.

Special positioners can also form part of automatic welding stations to provide movement of the weldment. Positioners can be integrated with welding robots to provide additional programmable axes for the robot system through coordinated movement or indexing. Available features and accessories include the following:

1. Constant or variable-speed drives,
2. Self-centering chucks or grippers,
3. Automatic indexing controls,
4. Powered elevation,
5. Through-hole tables, and
6. Digital tachometers for the measurement of rpm or surface speed (in./min [cm/min]).

Positioners for Robotic Welding Applications

The adaptation of positioners to robotic welding involves the integration of the motions of the robot with that of the positioner.[4] Two types of movement, indexing and coordinated motion, are typically used.

4. For more information on robotic welding, see Chapter 11, "Mechanized, Automated, and Robotic Welding."

Photograph courtesy of Pandjiris, Incorporated

Figure 9.15—Typical Powered-Elevation Positioner in the 135° Position

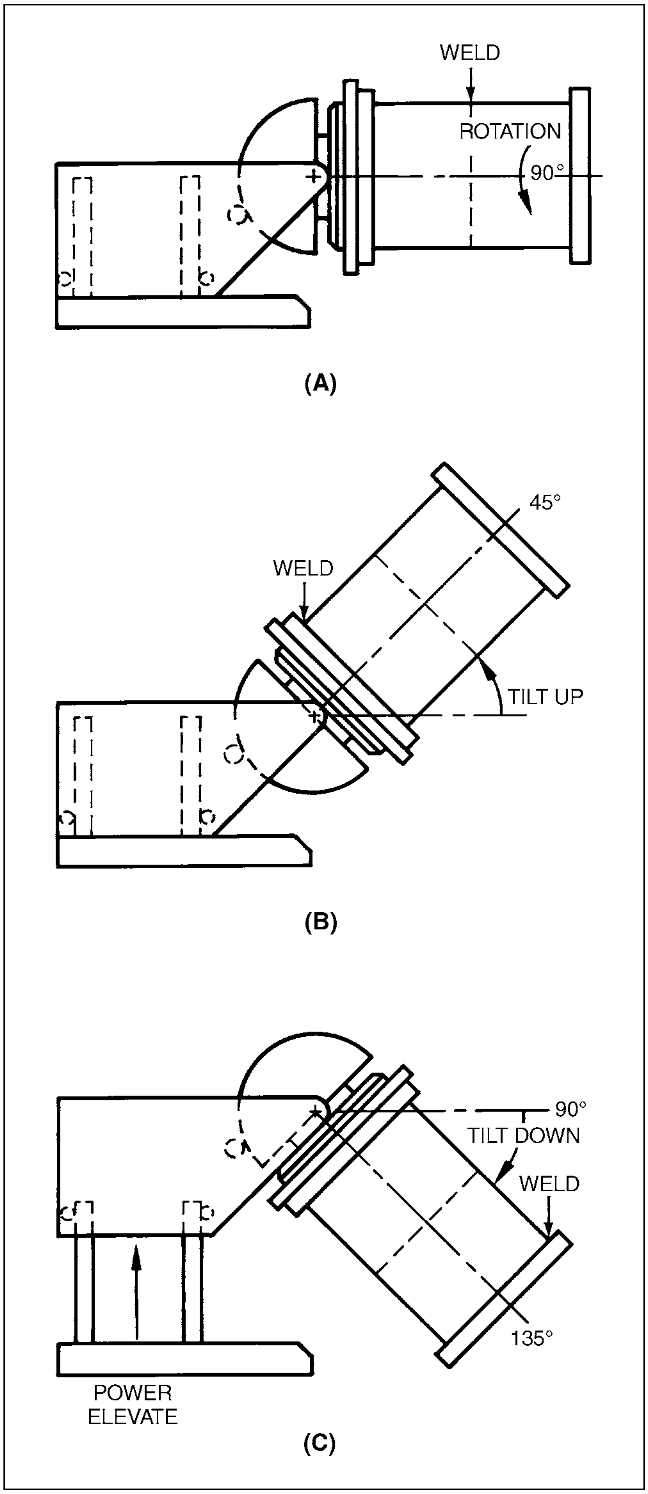


Figure 9.16—Powered-Elevation Fixture in Three Positions: (A) Girth Weld Position; (B) First Fillet Weld Position; and (C) Second Fillet Weld Position

A simple adaptation that can be made is exemplified by the turntable shown in Figure 9.12. The operator merely indexes the work into the robot work envelope by a 180° rotation of the turntable and starts the robot on its welding sequence. The operator then removes the welded assembly and sets up an unwelded assembly. When the robot completes its weld sequence, the robot arm returns to its "home" position. The operator then indexes the turntable 180° to locate the work in the robot work envelope and initiates the robot weld sequence.

As previously indicted, the robotic welding sequence begins with the location of the reference points that establish the coordinate system. Because the robot is "blind," the location of the weld seams or points must always be in the same relationship to the reference points on the fixture. The robot's tool center point should also be checked periodically and relocated if needed.

The interface between the positioner and the robot is provided by a human operator in this type of system. The operator recognizes when to index the turntable and when to activate the work sequence. Most robots are equipped with programmable inputs and outputs to recognize when a part is loaded, allowing the operator to clear the area prior to signaling the table to index.

Photograph courtesy of Pandjiris, Incorporated

Figure 9.17—Skyhook Positioner

To adapt a tilting-rotating positioner for use with a robot, as shown in Figure 9.18, more sophisticated controls are necessary. One system involves a robot with a programmable controller that has capacity to control devices in addition to the robot. The controller's capacities include adequate memory to store the motion programs for the robot and the positioner, additional input/output lines to send the motion commands to each device in sequence, and the ability to receive feedback from the device regarding the current status of the command execution. In some applications, the rotation and tilt axes provide coordinated motion through the robot controller. Some positioners can be programmed to manipulate the work to provide weld travel, but the most recent approach has been to vest all weld motion functions in the robot.

A combination turntable and coordinated motion positioner is shown in Figure 9.19. The two tables rotate about a center axis, and each table tilts and rotates about its own axis. An operator can load work onto one table, rotate the table toward the robot, and then initiate a programmed motion sequence for the positioner and the robot.

TECHNICAL CONSIDERATIONS

As each fixturing or positioning application is unique, the specific technical conditions relevant to each must be given careful consideration. These include the workpiece's center of gravity (CG), torque loading, issues related to the attachment of the weldment to the positioner, the tractive effort required by the turning rolls, and current conduction. These conditions are discussed in more detail below. Once the specific technical considerations have been determined, the proper sizing and the justification of weldment components and positioning devices can be made.

Center of Gravity

To use a positioner correctly, the operator must be cognizant of the weights of the weldment and the fixture, if used, and the location of the center of gravity of the total load. The farther the center of gravity of the load is from the axis of rotation, the greater the torque required to rotate the load. Also, the greater the distance from the surface of the table to the center of gravity, the larger is the torque required to tilt the load.

Consider a welding positioner that has the worktable tilted to the vertical position, like that shown in Figure 9.20. Figure 9.20(A) illustrates the worktable with no load. In Figure 9.20(B), a round, uniform weldment has been mounted on the worktable concentric with the axis of rotation. The center of gravity coincides with the axis of rotation. The torque required to maintain rotation of the weldment is only that needed to overcome friction in the bearings. However, torque is required to accelerate or decelerate the weldment. In Figure 9.20(C), an irregular-shaped weldment is mounted

Photograph courtesy of ABB Flexible Automation, Welding Systems Division

Figure 9.18—Robotic Workstation Using a Positioner Interfaced with a Robot

Photograph courtesy of ABB Flexible Automation, Welding Systems Division

Figure 9.19—Indexing Robotic Positioner

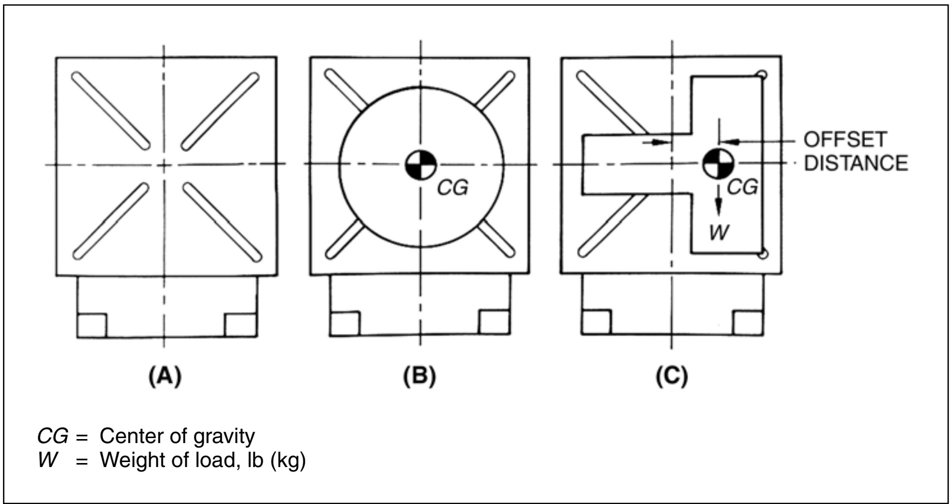


Figure 9.20—Effect of the Location of the Center of Gravity (CG) of a Workpiece on Rotational Torque

with its center of gravity offset from the rotation axis. In this case, torque is required to rotate the weldment.

The torque is equal to the weight multiplied by the offset distance (moment arm). If a 5000 lb (2200 kg) weldment has its center of gravity located 10 in. (254 mm) from the rotation axis, a minimum torque of 50,000 lb-in. (5600 N × m) is required to rotate it. The positioner must have enough drive capacity to provide this torque.

The location of the center of gravity of the load is also important in the tilting action of welding positioners. When the loaded table is in the vertical position, the load exerts a torque around the tilt axis, as shown in Figure 9.21. The torque, *T,* is equal to the weight of the load, *W,* multiplied by the distance from its center of gravity to the tilt axis of the positioner. The tilt axis of most conventional positioners is located behind the table face for the inherent overhang, *IO*. This length must be added to the distance, *D,* between the center of gravity of the load and the table face when calculating the tilt torque.

In other words, torque is calculated with the following equation:

$$T = W(IO + D) \tag{9.1}$$

where

T = Torque, lb-in. (N × m);
W = Weight of the load, lb (kg);
IO = Inherent overhang, in. (m); and
D = Distance from the table to center of gravity of the load, in. (m).

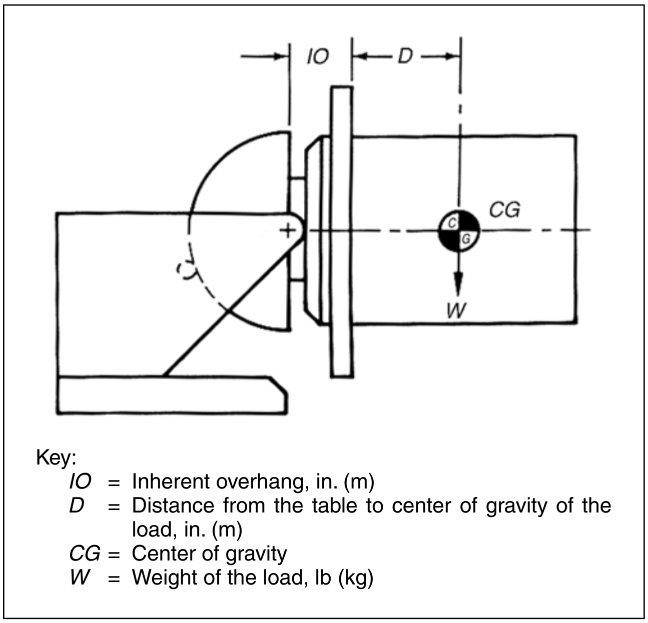
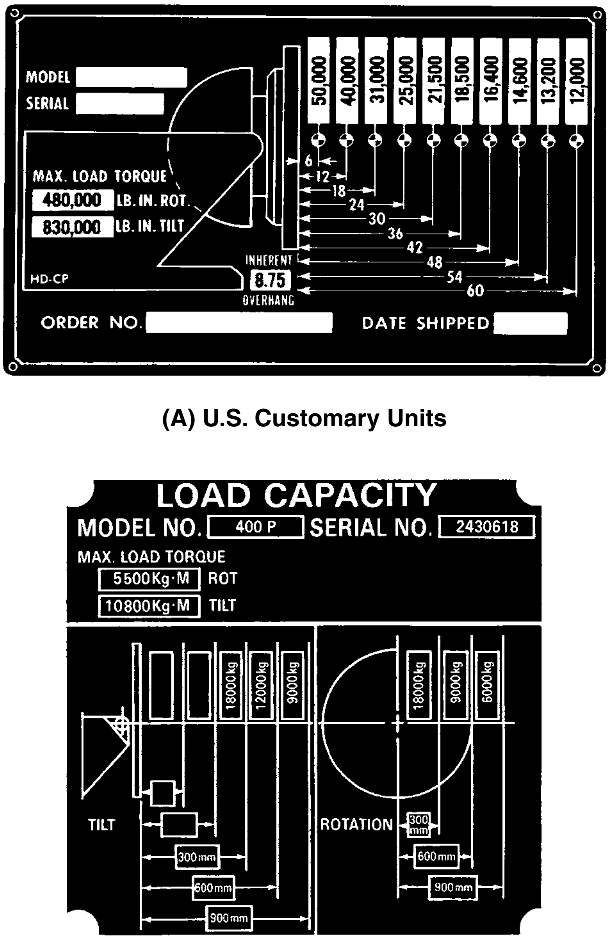


Figure 9.21—Effect of the Location of the Center of Gravity, CG, of a Workpiece on the Tilting Torque

The manufacturers of positioners customarily attach rating tables to their products. This rating table specifies the torque ratings in tilt and rotation, the inherent overhang, and the load capacity at various distances between the center of gravity of the load and the table. A typical rating table is shown in Figure 9.22.



(A) U.S. Customary Units

(B) SI Units

Figure 9.22—Typical Rating Table for a Tilting Positioner: (A) U.S. Customary Units and (B) SI Units

To select the proper positioner for a given weldment, the operator must determine the location of the center of gravity in order to ascertain the required torque. This can often be obtained from the engineering drawings or calculations provided by qualified welding personnel. Alternatively, it can be calculated or determined experimentally from a sample weldment.

Calculating the Center of Gravity. The center of gravity of a symmetrical weldment of uniform density is at the geometric center. For example, the center of gravity of a cylinder is located on the center axis at the midpoint of the length.

The center of gravity with respect to mutually perpendicular X, Y, and Z axes of a nonsymmetrical weldment can be determined by dividing the weldment into simple geometric shapes. The center of gravity of each shape is calculated utilizing formulas found in mechanical engineering handbooks or operating manuals. The location of the center of gravity of the total weldment with respect to selected X, Y, and Z axes is determined by a transfer formula of the form:

$$y = \frac{Aa_1 + Bb_1 + Cc_1 \ldots}{A + B + C \ldots} \tag{9.2}$$

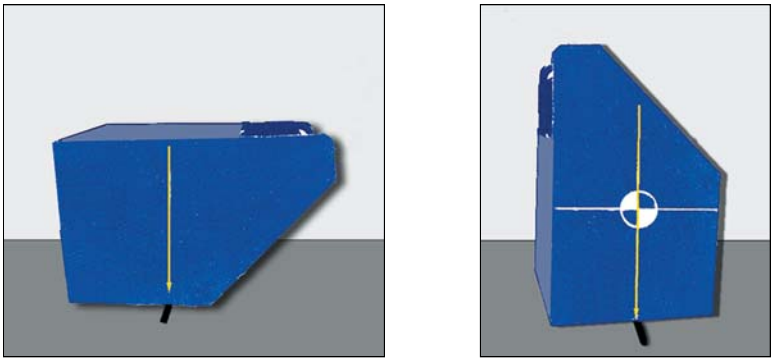
where

y = Distance from the X axis to the common center of gravity, in. (m);
A = Weight of Shape A, lb (kg);
a_1 = Distance from the X axis to center of gravity of A, in. (m);
B = Weight of Shape B, lb (kg);
b_1 = Distance from the X axis to the center of gravity of B, in. (m);
C = Weight of Shape C, lb (kg); and
c_1 = Distance from the X axis to center of gravity of C, in. (m).

Additional calculations are made as required to determine the location of the common center of gravity from the Y and Z axes. The shop must be able to locate the physical positions of the selected X, Y, and Z axes with respect to the weldment.

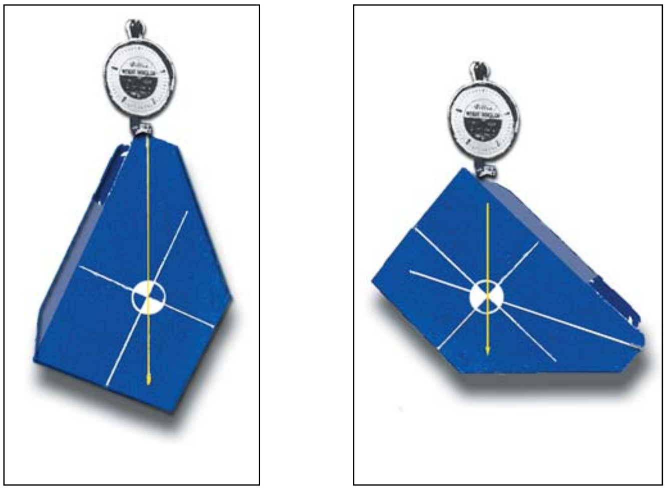
Finding the Center of Gravity by Means of Experimentation. Two practical methods are used to find the center of gravity without the need for calculations in the shop. The first method, which is shown in Figure 9.23, can be used to find the center of gravity of small box-shaped weldments. The weldment is balanced on a rod under one flat surface, as shown in Figure 9.23(A). A vertical line is made on the weldment above the rod. The weldment is then rotated to an adjacent flat surface, and the procedure is repeated, as shown in Figure 9.23(B). The center of gravity lies on a line passing through the intersection of the two lines. The location of the center of gravity in a third direction can be found by repeating the procedure with a flat surface perpendicular to the other two.

The second method used to determine the center of gravity experimentally employs a hoist. This technique is shown in Figure 9.24. The center of gravity of the weldment settles under a single lifting point. When a plumb bob is suspended from the lift hook, a chalk mark along the line passes through the center of gravity, as shown in Figure 9.24(A). A second lift from a different point on the weldment establishes a second line that



(A) (B)

Figure 9.23—(A) Determining the Center of Gravity (CG) by Balancing a Weldment on a Rod; (B) Alternate View



(A) (B)

Figure 9.24—(A) Determining the Center of Gravity (CG) of a Weldment Using a Hoist and (B) Alternate View

pinpoints the center of gravity at the intersection of the two lines, as shown in Figure 9.24(B). In each case, the chalk marks drawn while using the balancing bar method were left on the weldment to demonstrate that both methods indicate the center of gravity at the same location. A scale can be used during lifting to obtain the weight of the weldment.

Turning-Roll Tractive Effort

If the center of gravity of the workpiece is not on the rotation axis, the turning rolls must provide enough traction to transmit the required torque for rotation. The rated tractive effort for power rolls is the drive force available in pounds (kilograms) exerted at the surface of the wheels to rotate the workpiece. For turning rolls, the tractive effort required of the rolls can be calculated using the following formula:

$$TE = \frac{WD}{R} \tag{9.3}$$

where

TE = Tractive effort, lb (kg);
W = Weight of the load, lb (kg);

D = Distance from the axis of rotation of the load to the center of gravity, in. (m); and

R = Radius of the load or holding fixture, in. (m).

The tractive effort rating of the rolls should be about twice the calculated value to overcome drag conditions caused by workpiece misalignment and inconsistencies or additional idler rolls.

Attachment of the Weldment to the Positioner

With any type of positioning equipment involving a rotating or tilting table, the weldment must be fastened to the table. In the case of horizontal turntables, fastening serves only to prevent the weldment from being accidentally dislodged from the table. When the positioner table is used in positions other than horizontal, the fastening mechanism must firmly hold the weldment to the table in any work position.

Figure 9.25 illustrates the attachment of a weldment to a positioner table. When the positioner table is horizontal, as in Figure 9.25(A), the only force tending to move the weldment from the table is the centrifugal force of rotation. Attachment requirements are minimal at low rotation speeds. As the table is tilted, the weldment tends to slide off the table because a component of the weights acts parallel to the table, as shown in Figure 9.25(B). The attachments must have sufficient shear strength to prevent the weldment from sliding. As shown in Figure 9.25(C), the shearing force increases as

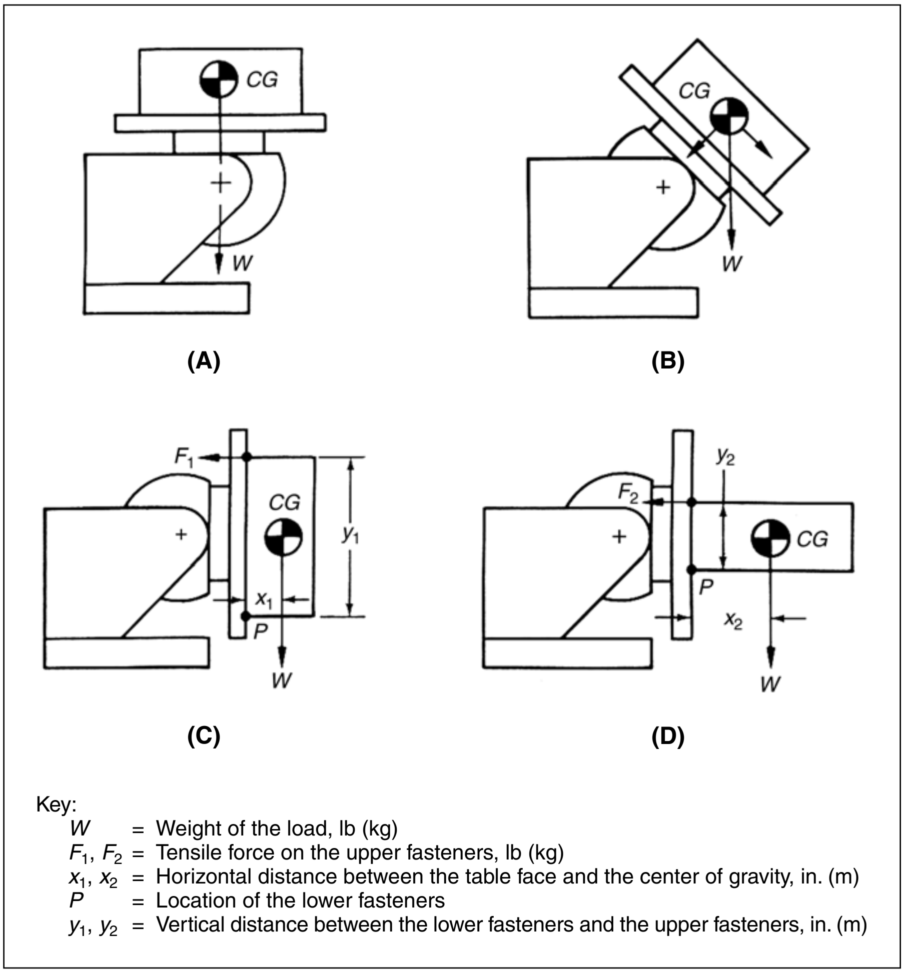


Figure 9.25—Effects of Tilting and Weldment Geometry on Positioner Fastener Requirements

the tilt angle of the table increases and is equal to the weight of the weldment at a 90° tilt.

During tilting, a point is reached at which the weldment would rotate about the lower fasteners if it were not restrained by the upper fasteners. The restraint results in tensile force on the upper fasteners [F_1 and F_2 in Figures 9.25(C) and (D)]. The amount of tensile force depends on the weight and geometry of the weldment.

The moment of the weldment about the lower fasteners, *P*, is the product of the weight, *W*, and the horizontal distance between the center of gravity and the lower fasteners, *x*. As the tilt angle increases, the horizontal distance increases. The weight moment is balanced by the moment of the tensile force on the upper fasteners.

Assuming that the weldments in Figure 9.25(C) and (D) are equal in weight, *W*, but that the weldment in (D) is longer and narrower than the one in (C), the force, *F*, can be determined by the following expression:

$$F = \frac{Wx}{y} \tag{9.4}$$

where

F = Tensile force, lb (kg);
W = Weight of the load, lb (kg);
x = Horizontal distance between the lower fasteners (P) and CG, in. (m); and
y = Vertical distance between the lower fasteners (P) and F, in. (m).

In both cases, x_2 is greater than x_1, and y_2 is less than y_1. Therefore, F_2 is greater than F_1. Accordingly, the attachments for the weldment in Figure 9.25(D) must be stronger than those for the weldment shown in Figure 9.25(C). In each case, all attachments must have sufficient strength to withstand both the shear force and the tensile force.

Two common methods, bolting and welding, are employed to hold a weldment on a positioner table. Most tables are provided with slots for mounting bolts, and some manufacturers supply T-nuts that match the slots. The largest bolts that fit the slots should always be used to avoid failure of the attachment. As a rule, a weldment with similar base dimensions and height can be safely mounted using four bolts of a diameter that is slightly smaller than the slot width in the table.

If a weldment is unusually tall with respect to its base dimensions, the force, *F*, on the mounting bolts should be calculated as described previously. The vertical distance between the lower fasteners, *y*, should be the minimum bolt spacing used. The calculation assumes that the entire load is on a single bolt and is therefore conservative. Generally, neither the table nor the workpiece is flat, which makes this assumption valid.

When properly tightened, the mounting bolts normally provide adequate shear resistance to prevent the weldment from sliding off the table. If any doubt exists as to whether the load is adequately restrained from sliding, steel stop blocks should be placed against the base of the weldment and tack welded to the table.

A weldment can be fastened to the table with temporary welds. The required size and length of each tack weld to carry the applied force, *F*, the shear load, or both should be determined as described in Chapter 5, "Design for Welding." When the job is completed, the tack welds are cut loose after the table is returned to the flat position or after the weldment is adequately supported by shoring or a hoist. If welding directly onto the positioner table is objectionable, a waster plate can be securely bolted to the table and the weldment welded to the plate. This waster plate can be replaced as needed.

Work-Lead Connection

Welding positioners that support a weldment on rotating members should provide some means of carrying the welding current from the weldment to a point on the chassis where the work lead is connected. It would be impractical to relocate the work lead continually on the weldment as the table is rotated.

Two techniques that are commonly used to conduct the welding current from the table to the base are sliding brushes and bearings. Either method can be satisfactory if properly designed, constructed, and maintained. Sliding brushes are usually made of a copper-graphite matrix, graphite, or copper. Several units are employed in parallel to provide adequate current-carrying capacity. The brushes are spring loaded to bear against a machined surface on a rotating element.

For proper operation, the brushes and rotating surface must be clean. The brushes must have the proper length, and the spring load must be adequate. The brushes should not be lubricated. As an alternative, the conducting bearings must be properly designed and adequately preloaded. If the bearing preload is lost because of mechanical damage, improper adjustment, or the overheating of the spindle, the bearings can be damaged by internal arcing between bearing surfaces. In normal usage, this system requires little maintenance, however.

Poor connections in the welding circuit tend to cause unexplainable fluctuations in arc length, varying joint penetration, or changes in bead shape. If the rotating connection on the positioner is suspected, it can be checked by measuring the voltage drop under actual arc welding conditions. The voltage drop should be low (0.1 V to 0.25 V), but more importantly, it should be constant. The cause of excessive voltage drop or fluctuation across the connection must be determined and corrected.

SAFETY CONSIDERATIONS

The use of mechanical positioners rather than manual labor to position weldments during welding reduces the likelihood of injury during welding operations. Nonetheless, the operation of industrial machinery requires the observance of safety codes and procedures. Safe welding practices begin with reading operations manuals; observing installation, maintenance, and operating instructions; and adhering to caution or warning statements for safe equipment operations. Safety considerations related to fixturing and positioning are discussed in more detail below.[5, 6]

Environmental Interference

Safe practice dictates that the area surrounding the workstation must be clear to avoid interference between the weldment and other objects in the area. Operators working in areas traversed by positioners or workpieces must pay close attention to obstructions at all times. Sufficient height must be provided for weldments to clear the floor. Manual or powered elevation in the base of the positioner is recommended for this purpose.

Operators must ensure that the floor and positioning devices are of sufficient capacity for the work being performed. The work area must be kept clean and dry, and stray chains, tools, cables, and rigging must be kept clear of the workpiece and attached obstructions at all times. Proper storage and access platforms for personnel should be provided to ensure that the equipment is not used as a work platform. Equipment guards must be in place, and no electrical circuitry or rotating machinery must be left exposed during operations. Precaution should be taken to observe positioning equipment that moves very slowly or very rapidly, depending on the application and the situation.

Fastening Loads

For safety, a weldment must be firmly mounted on a positioner to prevent its moving or falling off during welding and allied operations. The weldment or the fixture can be bolted or welded to the positioner table. In either case, the fastening mechanism must be strong enough to hold the work securely under any condition of tilt or rotation. The reaction loads at the fastening locations must be calculated or correctly estimated to ensure that the load is secured by properly designed fasteners.

Avoiding Instability

Positioners are designed to be stable when loaded within their rated capacity but may be unstable if overloaded. Tilting positioners may be unstable during tilting because of the inertia of the load. Injury to personnel or damage to equipment can be serious if an overloaded positioner suddenly tips during operation. For this reason, positioners must be fastened to the floor or other suitable foundation for safe operation. The instructions provided by the manufacturer concerning foundation design and fastening methods must be carefully followed to ensure safe installation.

The overloading of positioners cannot be condoned. When a positioner table is overloaded and then tilted to the 90° position, it may be impossible to return the table to the flat position because of insufficient power. Shop management must make every effort to ensure that the equipment is operated within its rated capacity to assure safe operation and long life. The accurate determination of the load, center of gravity, and eccentricity is imperative in the avoidance of overload. The safety features required in positioning equipment include thermal-limiting or current-limiting overload protection of the drive motor, low-voltage operator controls, a load-capacity chart, and emergency stop controls.

Turning rolls are particularly susceptible to instabilities such as overturning, creep, drag, and overload. Therefore, the safe practices associated with their use should include periodic stability checks. The workpiece and the rolls should be inspected to ensure clear, unobstructed rotation, paying close attention to any protrusion or interference. In addition, caution should be taken to avoid dropping a workpiece onto the rolls, which may damage the equipment and create an occupational hazard. Since turning rolls typically rotate at very slow speeds, operators must be sure to stop a turning roll when it is not in use.

Other Safe Practices

When using powered weldment clamping fixtures, a safety electrical interlock should prevent rotation (or elevation where applicable) until the clamping mechanism is fully locked to the weldment components. The use of proximity and limit switches is also advisable,

5. For additional information on safe practices, the reader is encouraged to consult Chapter 17 in this volume as well as American National Standards Institute (ANSI) Accredited Standards Committee Z49, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1, Miami: American Welding Society.
6. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

especially in the positioning of oversized loads to avoid overtravel or collision of the weldment with the floor or other obstructions.

Economic Considerations

With respect to cost, the use of a positioner can be either positive or negative, depending primarily on welding and handling costs. On the positive side are the high deposition rates, high operating factor, and high product quality that can be achieved when using a positioner to orient the work for flat-position welding. When used properly, positioners reduce the risk of accidents during the handling of weldments. On the negative side, handling costs are incurred in loading and unloading the positioner.

Deposition Rates

In arc welding, the highest deposition rates and the fewest passes are obtained when welding is performed in the flat position because gravity keeps the molten metal in the joint. Welds made with a minimum of passes generally contain less welding stress and associated distortion. It should be noted, however, that heat input limitations must be observed with some alloy steels. As the positioning of weldments increases the deposition rate and the arc time, this practice results in a significant reduction of welding costs.

Operator Factor and Set-Up Costs

The operator factor[7] is calculated from the ratio of the arc time to the total time that a welder dedicates to a weldment. In the absence of a positioner, the welder must manually reposition the weldment, wait for a crane operator to move it, and often weld in positions other than flat. Consequently, the operator factor is low, and welding costs are high. The operator factor is higher when a weldment is rapidly positioned for welding using a positioner. Nonetheless, the labor costs for both the safe loading and unloading of a heavy weldment on a positioner and for the repositioning of a weldment with a crane or other lift must be considered.

Welding Skill

Arc welding in the flat position requires less skill than other welding positions because this position makes it easier for the welder to control the molten weld pool. Therefore, welding positioning can reduce labor costs as the assembly can be easily manipulated for welding joints in the flat position.

For relatively short, small welds, it may be more economical to weld the joints in fixed positions than to reposition the weldment for ease of welding. In this case, welding costs are somewhat higher, but the overall labor costs are lower because of cost savings with respect to handling. However, quality welds performed in welding positions that are not optimal require additional operator training and skills, and operator fatigue tends to reduce productivity and weld quality. The cost of positioning equipment and material handling must be offset by cost savings in labor.

CONCLUSION

The advantages of weldment fixturing and positioning are significant. Positioning the weldment in the proper orientation minimizes operator fatigue during welding and cleaning operations, resulting in a minimum of discontinuities and weld repair. Welding in the flat position renders equal fillet legs, smoother weld beads, and improved penetration. With downhand welding, the effects of gravity improve the handling of molten metal to improve weld quality.

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7. For more information on the calculation of the operator factor, see Chapter 12 in this volume.

8. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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CHAPTER 10

MONITORING AND CONTROL OF WELDING AND JOINING PROCESSES

Photograph courtesy of Edison Welding Institute

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CHAPTER 10

MONITORING AND CONTROL OF WELDING AND JOINING PROCESSES

INTRODUCTION

Many welding operations rely on a skilled operator to monitor and control the process in order to produce quality welds. Human operators accomplish a variety of subtle tasks—weld placement, weld joint tracking, weld size control, and control of the weld pool, among many others—with relative ease. When human welders or operators are relieved of the welding process control function in favor of mechanized process control equipment, this subtle sense of the process is lost. However, the demands for increased productivity and improved quality, an increased emphasis on statistical process control, and the desire to remove the operator from the harsh welding environment continue to drive the need for real-time process monitoring and control.

The difficulties posed by measuring and controlling process variables in real time are major obstacles to the practical application of automatic controls. Welding processes are complex, and the variables that adversely affect the properties of the completed weldments are subject to change. The environment at the point of process application can be quite harsh. High temperatures, intense electromagnetic radiation, high electric and magnetic fields, molten metal spatter, and fumes are typically involved. Thus, sensors must be used to obtain physical information about the welding process.

Once an appropriate sensor has been selected, a monitoring device can be utilized to record and display the process variables. With respect to these variables, a process monitor can also be used to compare the output of the sensor to predefined parameter limits and sound an alarm when the measured value exceeds these limits. Process control goes a step beyond process monitoring in that adjustments are automatically made in the welding process to correct a variable that has deviated from the desired value.

This chapter provides information on the basic concepts and application of sensors, monitors, and controls in welding processes. The first section discusses the principles behind process sensing, monitoring, and control. The application of sensors, monitors, and process controls are then described in sections covering the arc, resistance, laser beam, electron beam, friction welding, and brazing processes.

PRINCIPLES OF MONITORING AND CONTROL

Welding operations can be described in terms of the four basic control elements. These, shown in Figure 10.1, are the welding process itself, the manipulated input variables, the disturbing input variables, and the process response variables. As illustrated in Figure 10.1, the basic welding process utilizes inputs of energy and mass to produce an output weld with the desired geometry and mechanical and microstructural characteristics.

MANIPULATED INPUT VARIABLES

The manipulated input variables are those which directly affect the process response variables. For exam-

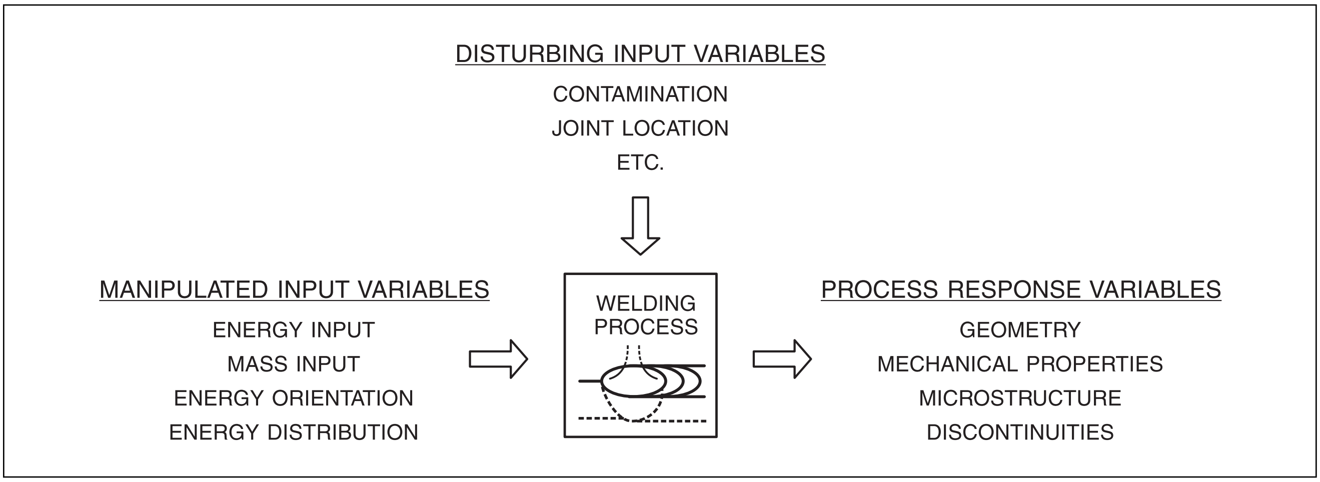


Figure 10.1—Flow Diagram of the Welding Process

ple, an increase in energy results in an increase in penetration (see below). The manipulated input variables can be set prior to starting the welding operation or altered during the process. Examples of preset variables include welding current, time and force (resistance welding), and voltage and wire feed speed (gas metal arc welding). Manipulated input variables also include arc length, travel speed, and electrode position and angle (arc welding processes), which may be adjusted manually during welding.

DISTURBING INPUT VARIABLES

The disturbing input variables are undesirable or unavoidable changes in those variables that have an effect on the process but are not normally controlled. The disturbing input variables include, for example, adjustments to the welding current due to a change in the input power to the welding machine; irregularities in sheet thickness, particularly in resistance spot welding; and variations in weld joint size and location in arc welding or joint gap in brazing.

PROCESS RESPONSE VARIABLES

The process response variables are the products of the welding process—the actual current, voltage, travel speed, and cooling rate, for example—that produce the desired weld properties, such as weld size, shape, microstructure, and soundness. For typical welding processes, it is impossible to sense most process response variables directly because no sensors exist for the in-situ measurement of mechanical properties or weld microstructure. Indirect measurement is therefore often performed of more practical control variables such as temperature, weld profile, weld size, penetration, and radiation.

SENSING DEVICES

In its most basic form, a sensor is a transducer that converts a property from one physical form to another, often to an electrical signal. Welding process sensors obtain information about the welding process by converting physical phenomena from the input and process response variables into signals that can be utilized by monitoring or control equipment. Signal conditioning, amplification, and isolation are often required before sensor output can be fed into a monitor or controller.

Sensors can be simple or complex in design. Examples of simple sensors include current shunts, which convert the current flowing in the welding circuit to a proportional voltage, and thermocouples, which convert temperature into a voltage signal. Complex sensors are composed of several individual sensors that operate together. An example is the machine vision sensor, which is used in robotic arc welding. This sensor is an entire subsystem, including a video camera (a transducer that converts light intensity into a video signal), a video signal digitizer, and a microprocessor, which extracts information from the video image. Machine vision sensors, which are described in more detail later in this chapter, provide information on the location and geometry of weld joints and the size and shape of weld pools.

The physical and operational characteristics of some sensors make them advantageous for use with specific welding processes as compared to other sensors. For instance, sensors that provide a direct measurement of the process variables are more desirable than those that provide indirect measurements. Sensing devices that require contact with the process or weldment are less desirable than those requiring no direct contact. In addition, sensors that can be applied from the face of the weld are more desirable than those requiring access to the interior or back of the weld. Overall, sensors that can be applied to multiple processes are highly desirable.

Table 10.1 presents an overview of the typical physical properties associated with the welding processes along with their corresponding sensors and measured units. These physical properties and their sensing devices are described in more detail below.

TIME

Time, the measurable duration of an event, is commonly measured in units of minutes or seconds. Arc welding may be partitioned into several events—upslope time, weld time, downslope time, and total arc time. The upslope time is the time interval during which the current changes continuously from the initial current to the welding current. The weld time is the time interval from the end of the upslope time to the beginning of the downslope time. The downslope time is the time during which the current is changed continuously from the welding current to the final current. The total arc time is the time interval for which a welding arc is sustained.

Other welding processes such as resistance welding are also partitioned into discrete intervals that can be measured in units of time. In resistance welding, time periods are often measured by the number of 60-hertz (Hz) cycles of alternating current.

TEMPERATURE

Many different types of transducers are available for temperature measurement. These include thermocouples, thermistors, resistive-temperature devices, optical pyrometers, photon detectors, and thermal imaging

Table 10.1
Common Sensors and Units of Measure

Physical Property	Sensor(s)	Units
Time	Timer, counter	Second, cycle*
Temperature	Thermocouple, resistive-temperature device, thermistor, pyrometer	Fahrenheit (Celsius)
Force	Load cell, piezoelectric, linear variable differential transformer, and capacitive force sensors	Newton, pound (kilogram)
Pressure	Displacement- and diaphragm-type pressure sensors	Pounds force per square inch (kilopascal)
Flow rate	Differential pressure flow meter, mechanical flow meter, mass flow meter	Cubic feet per minute (liters per minute)
Electric current	Current shunt, Hall-effect sensor, Rogowski coil	Amperes
Electric potential	Voltmeter	Volt
Displacement	Potentiometer, voltage differential transformer, inductive and capacitive sensors; synchro; resolver; encoder; ultrasonic sensor; machine vision sensor	Inch (millimeter)
Velocity	Potentiometer; voltage differential transformer; inductive and capacitive sensors; synchro; resolver; encoder; ultrasonic sensor; machine vision sensor	Inches per minute (millimeters per second)
Acceleration	Potentiometer; voltage differential transformer; inductive and capacitive sensors; synchro; resolver; encoder; ultrasonic sensor; machine vision sensor	Inches per minute squared (millimeters per second squared)
Radiation (visible light, infrared, ultraviolet)	Photodiode, phototransitor, solar cell sensor	Lumen (candela)
Acoustic (sound) energy	Microphone	Decibel

*Cycle = Interval of time based on frequency.

cameras. Thermocouples, thermistors, and resistive-temperature devices can be used simply as contact sensors or as part of more complex noncontact sensors. Examples of the latter include thermopiles, bolometers, and radiometers, which measure radiant thermal energy. The temperature sensors most commonly used for welding applications typically measure the temperature range between room temperature and the melting temperature of the material being welded.

Thermocouple

Thermocouples are simple temperature sensors that consist of two dissimilar materials in thermal contact. The operation of the thermocouple is based on the Seebeck, or thermoelectric, effect. This effect produces a voltage between two thermocouple junctions that are at different temperatures. The voltage, normally in millivolts (mV), is proportional to the temperature difference between the junctions. Thermocouples are available in a variety of configurations and types as well as for application in a variety of temperature ranges. A common thermocouple, the K-type, is made with nickel-chromium and nickel-aluminum wires and is applicable to environments ranging from room temperature to 2280°F (1250°C).

Thermistor

Thermistors are temperature-sensitive resistors fabricated from semiconducting materials whose resistance varies inversely with temperature. These devices are typically used when high sensitivity is required. The resistance of a 5000 ohm (Ω) thermistor may decrease by approximately 11.1 Ω for each degree Fahrenheit (20 Ω/°C) increase in temperature. The usable range of a thermistor is typically from room temperature to 620°F (327°C).

Resistive-Temperature Device

Resistive-temperature devices (RTDs) consist of resistive elements that are formed from semiconducting materials that exhibit a positive coefficient of resistivity with a change in temperature. These sensors are stable and provide a reproducible response to temperature changes. Resistive-temperature devices are available for application in a variety of temperature ranges between room temperature and 1832°F (1000°C).

Optical Pyrometer

Optical pyrometers are noncontact devices that measure the thermal radiation emitted by a source. The radiation may be in the infrared or visible light range, depending on the temperature. Infrared pyrometers employ the infrared portion of the spectrum by using a thermal detector to measure the temperature of the surface of the body emitting the infrared waves.

Photon Detector and Thermal Imaging Camera

Photon detectors measure temperature by generating a voltage that is proportional to the density of the photon flux impinging on the sensor. Thermal imaging cameras are sensitive to infrared radiation. They are used for temperature sensing and more complex measurements of temperature distributions.

FORCE

Force sensors are based upon the principle that a body will deform in proportion to an applied force. The force is indirectly determined by measuring the physical deformation.

Load Cell Sensors

The load cell sensor consists of a structure (a cantilever beam, shear beam, diaphragm, proving ring, or column) that deforms when subjected to a force and a network of strain gauges that produce an electrical signal proportional to this deformation. The choice of structural element is based primarily upon the physical size constraints of the sensor and the maximum force to be applied.

Other Force Sensors

Other force sensors include the piezoelectric, linear variable differential transformer (LVDT), and capacitive force sensors.

PRESSURE

Pressure sensors measure the distortion produced by pressure acting upon a deformable member. They convert this distortion into an electrical signal through a measurement of displacement, strain, or piezoelectric response.

Displacement- and Diaphragm-Type Pressure Sensors

Displacement-type pressure sensors employ a Bourdon tube as the elastic element and a LVDT as the sensor. The C-shaped Bourdon tube has an oval cross section that tends to straighten as internal pressure is applied.

One end of the tube is fixed, while the other is free to move. As pressure is applied to the Bourdon tube, the displacement of the free end is converted to a voltage by the LVDT.

Diaphragm-type pressure sensors utilize either a clamped circular plate (diaphragm) or a hollow cylinder as the elastic element and electrical resistance strain gauges as the sensors. As pressure increases, the diaphragm deforms, causing the strain gauges to change resistance.

Piezoelectric-Type Pressure Sensor

Piezoelectric-type pressure sensors use a piezoelectric crystal as both the elastic element and the sensor. The crystal is enclosed in a cylindrical shell that has a thin pressure-transmitting diaphragm on one end and a rigid support base for the crystal on the other end. As pressure is applied to the face of the crystal in contact with the diaphragm, an electrostatic charge is generated. The magnitude of the charge depends on the pressure, the size of the crystal, and the orientation of the crystal's axis.

FLOW RATE

The objective of flow rate measurement is to determine the quantity of flow of a liquid or gas (e.g., cooling water or shielding gas). In some instances, a flow meter returns this information directly, but in most cases, the signal is derived from some property of the flow, such as volume, heat transfer rate, or momentum flux. In most cases, the flow meter signal requires correction for pressure, temperature, or viscosity before the flow rate can be determined. The measurement of flow can be accomplished using many different physical principles. However, the majority can be classified as volume or mass flow rate measurements.

Differential Pressure Flow Meters

Differential pressure flow meters are the devices most commonly used for the measure of flow volume. A constriction in the flow path results in a corresponding change in the velocity and pressure of the fluid. The pressure differential can be measured using pressure gauges. Differential pressure flow meters include the Venturi meter, the flow nozzle meter, the orifice meter, and the elbow meter.

Mechanical Flow Meters

Mechanical flow meters are placed in the path of flow and are activated by the flow volume or rate. The turbine flow meter is the most common type of mechanical flow meter. This meter consists of a multibladed rotor suspended in the flow with the axis of rotation parallel to the direction of the flow. The flow impinges on the blades and causes them to rotate at an angular velocity that is proportional to the flow rate. The speed of rotation of the turbine can be measured with a variety of speed-sensing techniques.

ELECTRIC CURRENT

The current shunt, the Hall-effect current sensor, and the Rogowski coil are commonly used current-sensing devices.

Current Shunt

The current shunt is a resistor that has a small, precisely known resistance value. According to Ohm's law, the voltage output across the shunt is proportional to the current flow through it. An advantage of the current shunt is that it is relatively inexpensive. However, some applications may require an amplifier to boost the millivolt output from the shunt to a level that is compatible with a monitoring or control device. A disadvantage of the current shunt is that it is electrically connected to the welding power circuit. Without proper signal conditioning and electrical isolation, the voltage of the shunt relative to ground may cause damage to the device to which it is connected or produce erroneous measurements.

Hall-Effect Current Sensor

The Hall-effect current sensor is an electronic device that indirectly senses current by measuring the strength of the magnetic field produced by the current flow. The probe simply clamps around the outside of the insulated conductor carrying the current. A distinct advantage of the Hall-effect device is that no electrical contact is required with the power circuit. The Hall-effect current sensor is significantly more expensive than the current shunt, however.

Rogowski Coil

A Rogowski coil is a device used to measure alternating current in resistance welding. It consists of wire that is tightly wound around a nonconducting belt of uniform cross section. The belt is then wrapped around the resistance weld current-carrying conductor. The voltage output of the coil is proportional to the rate of change of the current. Many commercially available coil/integrator combinations can provide outputs of the root-mean-square (RMS) current, peak current, waveform, and the fraction of time the current was on during each half cycle during the weld.

Like the Hall-effect sensor, the Rogowski coil is a nonintrusive current measurement device since it does not interrupt the conducting circuit. A common Rogowski coil and meter combination is shown in Figure 10.2.

Electric Potential

The measurement of voltage is simple for most welding processes, including arc and resistance welding. Sensing wires are attached to the points where voltage measurement is needed. In the arc welding processes, voltage is normally measured between the electrode holder or welding torch and the workpiece. The voltage that is measured in this manner may be properly termed the *process voltage* as it includes the voltage drops of the arc column, the arc anode and cathode, the electrode, and part of the workpiece or fixture. Typically, a voltage divider and isolator are used to condition the signal before it is attached to a monitor or controller.

Other electrical parameters such as inductance, resistance, and reluctance can be calculated from voltage and current signals using relations such as Ohm's law.

Figure 10. 2—Rogowski-Type Current Sensing Coil and Meter Combination

DISPLACEMENT, VELOCITY, AND ACCELERATION

Many methods have been developed to measure linear and angular displacement, velocity, and acceleration. The mathematical relations between displacement, velocity, and acceleration suggest that any one measure can be obtained from the others by integration or differentiation.

Linear and Rotary Potentiometers

The simplest displacement transducers are the linear and rotary potentiometers, which are excited by a direct-current (dc) power source. A potentiometer consists of a resistive element and a movable contact that can be turned by mechanical means. These components may be connected to deliver an output voltage that is proportional to a linear or a rotary displacement varying between zero and some maximum distance.

Linear and Rotary Variable Differential Transformers

The linear variable differential transformer (LVDT), used for linear applications, and the rotary variable differential transformer (RVDT), used for angular applications, provide an alternating-current (ac) output signal that is proportional to a physical distance or displacement. LVDTs and RVDTs have one primary winding and two secondary windings wrapped on the same form. The form, which is hollow, contains a magnetic core that is free to slide inside it. These devices are built so that the voltage difference between the two secondary winding voltages is proportional to the displacement of the core. The LVDTs and RVTDs can also be used to measure velocity and acceleration.

Inductive Sensors

Inductive sensors measure small displacements without having to make contact with the workpiece. The sensor must be in close proximity to a material that is electrically conductive. These sensors have a cylindrical jacket with a multiturn coil of wire implanted very close to the surface of the sensing probe.

Several techniques exist for the measurement of the distance between the sensor and the surface. One method senses the changes in inductance of the sensor coil caused by changes in the electromagnetic coupling between the sensor and the target. Another technique utilizes the eddy current phenomenon by exciting the coil with a radio frequency signal and detecting the loss of signal strength.

Capacitive Sensors

Capacitive sensors can also measure distance without contact. Because their sensitivity is inversely proportional to the distance measured, they are especially suited for short distances. Using Faraday's law, a capacitive sensor can sense distances through changes in distance, area, or permeability, depending on sensor configuration.

Encoders

An encoder is a device used to generate digital linear or angular displacement data. It consists of an encoding mast with incremental or absolute codes excited by optical, electrical, or magnetic energy. The output of the encoder is a pulse train. The total number of pulses defines the distance traveled from a "home" location. The number of pulses in a given time defines velocity. While incremental encoders are less expensive than absolute encoders, they may lose displacement information if a loss of power occurs. Displacement information can always be inferred with absolute encoders.

Synchros and Resolvers

Synchros and resolvers are rotary transformers whose coupling varies as a function of rotor displacement. Consisting of a stator housing and a rotor core, synchros and resolvers are similar to electric motors. The rotor is excited with a reference alternating current, which induces voltage in the stator coils. Voltage outputs from these devices are proportional to the sine and cosine of the shaft angle. The displacement of the rotary shaft can be inferred from the voltage ratio between the coils.

Ultrasonic Ranging Sensors

Ultrasonic ranging sensors measure distances using pulses of acoustic energy. These noncontact sensors consist of a transmitter and a receiver. Pulses of acoustic energy are emitted from the transmitter, usually at frequencies above audible levels. Reflected acoustic energy from the target object is detected, and the resulting time of flight is used to determine the distance. Several variations of this device utilize piezoelectric, magnetostrictive, or capacitive transmitters and receivers.

Optical Displacement Sensors

A wide variety of optical displacement measurement methods are also available. These methods range from Moire gratings, which provide interference patterns for measuring strain, to high-speed photography, which employs video digitization and a high-speed computer to calculate displacement.

The laser range-finding sensor is an optical technique that uses laser light and a linear detector to determine displacement using the principle of triangulation. Variations of this technique use Doppler (phase-shift) or modulation (time-of-flight) techniques to determine displacement.

Laser-based structured-light machine vision sensors are more complex. They use the principle of triangulation to measure the distance along a line of laser light projected onto the surface. These sensors measure the profile of a surface along the laser line in two dimensions. Three dimensions can be measured by moving the sensor and taking measurements at multiple locations.

RADIATION

Radiation is a generic term that denotes the ultraviolet (UV), visible (light), and infrared (IR) portions of the electromagnetic spectrum. Radiation sensors and detectors are semiconductor devices that convert the incident radiant energy into an electrical output. Several types of detectors are available. These include photodiodes, phototransistors, and solar cells. Accessories that can be used with optical detectors include optical filters, lenses, and fiber-optic cables. Thermal radiation sensors are described above in the section titled "Temperature."

ACOUSTICS

A microphone, or acoustic pickup transducer, converts the mechanical energy of acoustic waves into an electrical signal that can be analyzed. Acoustic energy may take the form of sound in the audible or ultrasonic range. It may be airborne or transmitted within the material being welded. Signal conditioning such as filtering or amplification may be used before the waveform is analyzed.

PROCESS INSTRUMENTATION

Welding process instruments are devices that use one or more sensors to collect and display information about the welding process variables. Several classes of instrumentation technology can be used with welding processes. These include data displays, data recorders, data loggers, and process monitoring systems.

DATA DISPLAYS

Data displays are analog or digital meters or gauges that convert the signal from a sensor into engineering units and display the results. Most welding equipment has one or more built-in data displays, such as those used to indicate voltage, current, and wire feed speed.

DATA RECORDERS AND LOGGERS

Data recorders are analog devices that allow the storage and display of process information as a function of time. Oscilloscopes and strip chart recorders are examples of data recorders. Data loggers are similar to data recorders except that these devices convert analog sensor signals into digital format before processing the information with digital computer technology.

PROCESS MONITORING SYSTEMS

Welding process monitoring systems are computer-based systems that provide data acquisition and storage functions along with significant data-processing capability. This data-processing capability may include statistical analysis, complex signal filtering, and limited decision-making capability. For example, a weld process monitoring system can compare measured data to predefined limits. If a threshold value is exceeded, the monitor sounds an alarm to alert the operator or disable the process. Some monitors have the capability to collect and store data for a number of welds to allow off-line analysis of process trends.

PROCESS CONTROL SYSTEMS

A controller or control system regulates a process or equipment to produce the desired response. Controllers typically control the sequence of operations; the process variables; multiple schedules; motion, in the case of robotic or automatic equipment; and other dedicated control functions. They are used at every level within the factory. At the highest level, a supervisory controller may manage the overall operations of an entire welding production line. At a lower level, a robotic controller performs motion control of a welding robot arm.

The term *controller* can also describe one of several elements of a welding system. At the lowest level, an open-loop controller can control the current, force, and time of a resistance weld. A slightly higher level might involve the closed-loop feedback control integrated into welding equipment to control welding variables such as the current or wire feed speed.

In this chapter, the term *process control* is used to describe the real-time regulation of one or more control variables of a welding process. The broadest overall classification separates control systems into two fundamental types—open-loop and closed-loop control. Closed-loop control can be further classified as feedback or feedforward control.

OPEN-LOOP CONTROL

An open-loop system provides no measurement of the process response variables and therefore makes no subsequent use of these variables to adjust the process to conform to the desired output. The block diagram presented in Figure 10.3 illustrates the basic open-loop process control system.

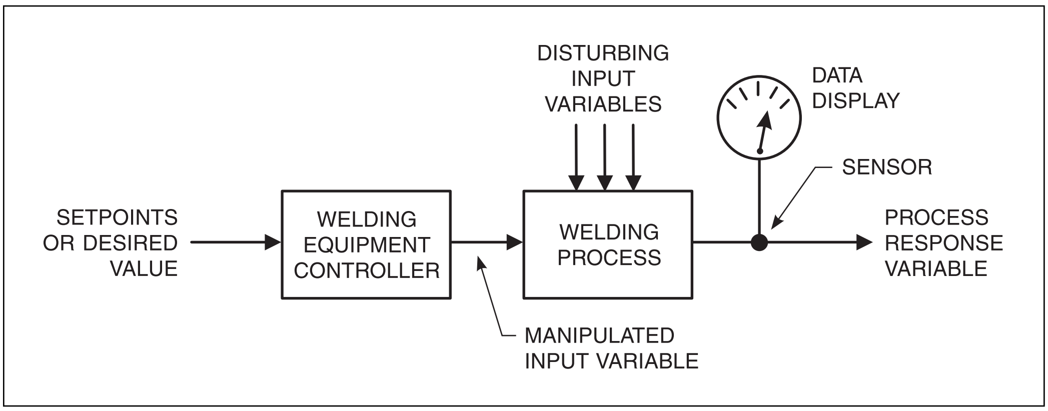


Figure 10.3—Open-Loop Control of the Welding Process

An example of open-loop control is a wire feeder for a semi-automatic arc welding process. The desired wire feed speed is set on the welding equipment controller. In the event that some disturbing input acts upon the process, it is not possible for the controller to sense that the process output may have deviated from the desired value. For example, the controller cannot sense whether an obstruction in the welding torch causes a decrease in wire feed speed from that set on the controller. For open-loop control to regulate a welding process properly, disturbances to the process must be eliminated by means of preweld preparation, fitting and fixturing, or the maintenance of equipment.

CLOSED-LOOP CONTROL

In order to maintain the process output at the desired value regardless of the effect of disturbing inputs, the controller must have information about the actual state of the process. In other words, the process control loop must be closed. Implementation of a closed-loop control system involves three elements: (1) sensing, (2) a process model, and (3) control techniques. The first of these elements, sensing, is discussed above. Closed-loop feedback control is accomplished by using a sensor that provides information about the process response variables during welding. This type of system is shown in Figure 10.4.

Arc voltage control is an example of feedback control. Arc voltage is sensed, and arc length is varied by manipulating the height of the welding torch with respect to the weldment until the desired arc voltage is achieved.

If a sensor provides information about disturbances that are about to influence the process, such as those caused by disturbing input variables, the closed-loop system is considered a feedforward control. An example of a feedforward control is joint tracking during arc or electron beam welding. In this case, when the sensor detects that the trajectory of the torch or beam is deviating from the centerline of the weld joint ahead of the point of welding, it provides corrective movement commands to maintain the proper joint alignment.

When the input-output relationship of a process can be modeled mathematically or determined precisely by measuring the output response due to changes in input variables, the controller can be designed using classical control techniques and empirical or analytical models. If the process is complex and only a limited number of input-output pairs of process data can be obtained, artificial intelligence techniques such as fuzzy control may provide the basis for a controller. Hybrid control systems that combine classic and artificial intelligence techniques are also available.

In formal control theory, adaptive control involves the use of a controller that can change its character to adapt to functional changes in the process being controlled. The term *adaptive control* is defined in the American National Standard *Standard Welding Terms and Definitions,* A3.0:2001, as “pertaining to process control that automatically determines changes in welding conditions

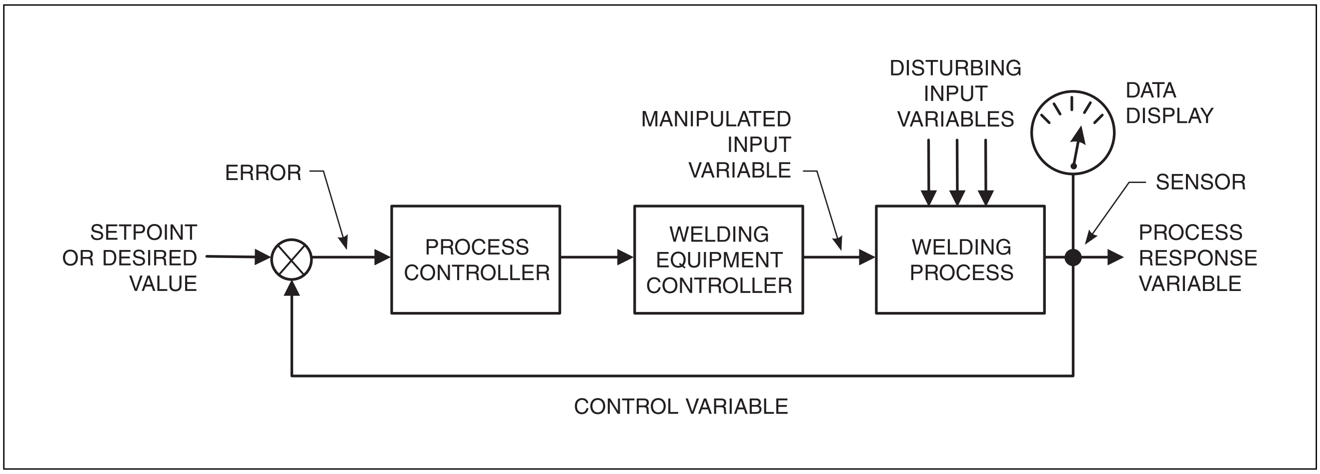


Figure 10.4—Closed-Loop Feedback Control of the Welding Process

and directs the equipment to take appropriate action.”[1, 2] Thus, adaptive control is simply closed-loop control, and it can be applied to a number of welding process control techniques.

MONITORING AND CONTROL SYSTEMS

Many different types of process monitoring and control systems have been developed. All the techniques discussed below are either commercially available, under development as a commercial product, under ongoing research as a potential product, or being developed by a particular manufacturer for use in their own production. The following discussion of monitoring and control systems is categorized according to welding process. The processes discussed are the arc welding processes, resistance welding, laser beam welding, electron beam welding, friction welding, and brazing.

ARC WELDING PROCESSES

This section describes the techniques that are commonly used for arc welding monitoring and control. Table 10.2 lists the arc welding process variables for which sensors, monitors, and controls are applied. The publication *Welding Processes*,[3] Volume 2 of the *Welding Handbook,* 8th edition, includes a description of these process variables and their influence on each of the arc welding processes.

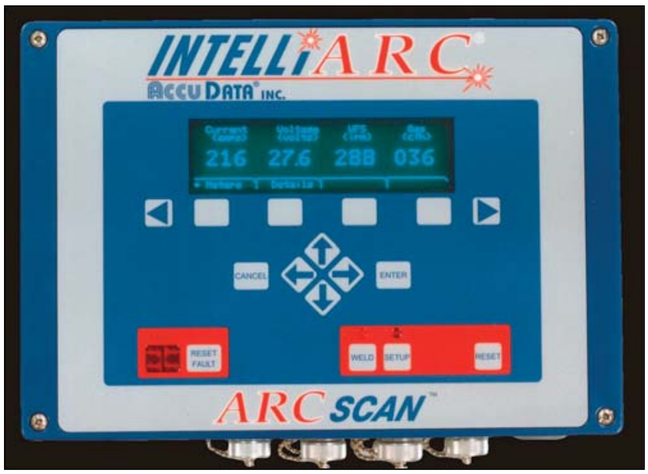
Table 10.2
Variables Commonly Sensed in Arc Welding

Variable	Monitor	Control
Current	✓	✓
Arc length	✓	✓
Arc voltage	✓	✓
Arc time	✓	✓
Wire speed	✓	✓
Travel speed	✓	✓
Shielding gas flow	✓	✓
Weld zone temperature	✓	✓
Arc light	✓	
Arc sound	✓	
Weld joint location	✓	

Monitoring Systems

The data collected by welding monitors can be used for statistical process control, welding procedure development, operator training, equipment monitoring, and process validation. Arc welding monitoring systems are typically connected via current, voltage, and wire feed speed sensors. The travel speed of mechanized or automatic welding operations, the shielding-gas flow, and the preheat and interpass temperatures can be monitored with the appropriate additional sensors and recording devices.

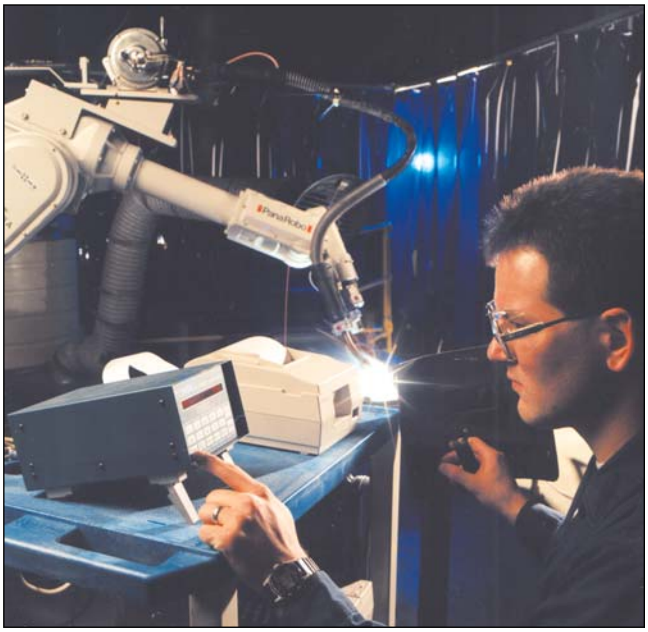
Control limits can be defined for each variable, and a monitor sounds an alarm when these limits are exceeded. The welding operator typically responds to the alarm and corrects the problem before welding is resumed. Some monitors can also collect and store data from a series of welds. An example of a commercially available arc welding monitor is shown in Figure 10.5. Figure 10.6 shows a monitor with a printer read-out used to monitor robotic arc welding operations.



Photograph courtesy of Accudata, Incorporated

Figure 10.5—Commercial Arc Welding Monitor

1. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society, p. 11.
2. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. O’Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.



Photograph courtesy of the Edison Welding Institute

Figure 10.6—Arc Welding Monitor Used for a Robotic Arc Welding Operation

A second type of monitoring system uses vision sensors to measure weld features after welding. Either machine vision sensing or laser-based machine vision sensing can be used to acquire images of the finished weld. A computer analyzes these images and extracts key features of the weld. These systems can measure weld features such as leg length, theoretical throat, concavity or convexity, toe angles, toe radii, and joint features such as gaps, tacks, and workpiece angle. Vision systems can also detect and quantify surface-breaking discontinuities such as cracks, undercut, or porosity. However, these systems do not provide any information on subsurface features such as penetration or sidewall fusion. Hand-held and robotic-controlled systems are available.

Control of Basic Process Variables

While all arc welding systems have some form of open-loop control, the use of closed-loop control has gained widespread application, especially with highly automated systems. This section discusses commonly applied techniques such as arc length control for gas tungsten arc welding and joint finding and joint tracking for robotic gas metal arc welding. Also discussed are recent concepts such as metal transfer mode control and weld geometry control.

Arc welding equipment that provides closed-loop control of one or more process variables is available for semi-automatic, mechanized, and automatic arc welding operations. Control of the welding current, voltage, shielding gas, and wire feed speed is accomplished using appropriate sensors to measure actual values of these variables and regulate them to set limits. Figure 10.4 presents a block diagram of this type of control. Mechanized and automatic welding equipment can also be designed for closed-loop control of the welding speed, arc-on time, and shielding gas flow rates as well as the preheat and interpass temperature of the weldment.

Arc Length and Voltage. Arc length control, also referred to as *arc voltage control (AVC),* is commonly applied to mechanized or automatic gas tungsten arc welding. The objective of arc length control is to maintain a constant arc length in spite of the fact that the distance between the torch and weld pool may change. This change can occur because of variations in joint location with respect to the torch due to component tolerances, thermal distortion, or improper joint tracking. Variations in the surface of the weld pool due to the sag of the pool during full-penetration welding or an increase in the height of the pool due to buildup may also cause variations in arc length.

Arc length control is achieved by measuring the changes in arc length and then adjusting the torch height using an automated manipulator. Arc length is commonly determined by measuring the arc voltage. Arc voltage is proportional to arc length by means of the following relationship:

$$E_A = E_O + \frac{\Delta E_A}{\Delta \text{length}_A} \text{length}_A \tag{10.1}$$

where

E_A = Arc plasma voltage, V;
E_O = Combined arc anode and cathode voltages, volts (V); and
$\Delta E_A/\Delta \text{length}_A$ = Arc plasma voltage gradient that is primarily a function of the composition of the shielding gas, in. (mm).

The use of the arc as the sensor for arc length is simple and preferred because no external sensing device is required. It should be noted, however, that arc voltage sensing has limitations for some pulsed-current applications and may have poor sensitivity at short arc lengths.

It has also been shown that arc sound and arc light emissions during gas tungsten arc welding are proportional to the arc voltage and arc length. Control systems based on arc sound use high frequency current pulses to modulate the arc and measure the frequency range of the sound pressure from the arc. Likewise, arc light has been used to control arc length by measuring either a broad spectrum of light or a specific band of wavelengths using basic photoelectric detectors.

The distance from the electrode to the surface of the workpiece in gas tungsten arc welding and the contact tip-to-work distance for the gas metal arc welding or flux cored arc welding processes can be measured with other techniques as well. These include machine vision, laser range finders, and inductive or capacitive proximity sensors.

Joint Finding. With some automatic or robotic arc welding operations, maintaining the proper alignment of the welding arc (torch) with the weld joint is often problematic. The dimensional tolerances of component parts, variations in edge preparation and fitup, distortion during welding, and other dimensional variations can affect the exact position and uniformity of the weld joints from one assembly to another. Feedforward process control is achieved by sensing the orientation of the weld joint and adjusting the torch path accordingly.

Touch sensing uses the welding electrode itself as a contact probe to find the joint or weldment. A low-voltage dc signal is applied between the probe and the workpiece. The electrode is moved in a search pattern in the vicinity of the joint using several axes of motion. A voltage change identifies the moment at which the electrode touches the surface. The coordinates of this point are noted, and the search resumes. Once the orientation of the joint has been determined from several points on the weldment, the trajectory of the torch can be programmed to follow the joint precisely.

The accuracy of joint finding depends on the accuracy of the manipulator or robot, the speed used during searching, and the response time of the sensor control circuit. In addition, other robot-related factors such as tool definition accuracy affect overall accuracy of the sensor system. Nonconductive material on the weldment surface or the probe can also adversely affect the performance of the joint-finding system.

The selection of the probe used for joint finding is of particular importance and depends on the application and speed of the sensing operation. The advantage of using the welding electrode for joint finding is the elimination of inaccuracies that may occur due to position translations that are required when other separate probes are used. A disadvantage of using the electrode is that it is easily bent during searching. In addition, the position of the electrode may change as the robot and cables are moved.

The torch nozzle provides a fixed probe, but spatter on the nozzle can adversely affect accuracy. In addition, the nozzle is not compliant, which could result in a bent welding torch. The advantages of a probe are that it can be made compliant and that it is separate from the welding torch. However, both the torch nozzle and a secondary probe require additional position translations, which can reduce accuracy. The probe may also be at a disadvantage if it restricts access in some cases.

A variation of the touch-sensing technique is used to locate the surface of the weldment for gas tungsten arc welding. A small voltage potential is applied to the electrode, which is moved into contact with the surface of the weldment. The voltage change is used to sense the surface. Once the surface is located, the torch is retracted a specified distance before welding.

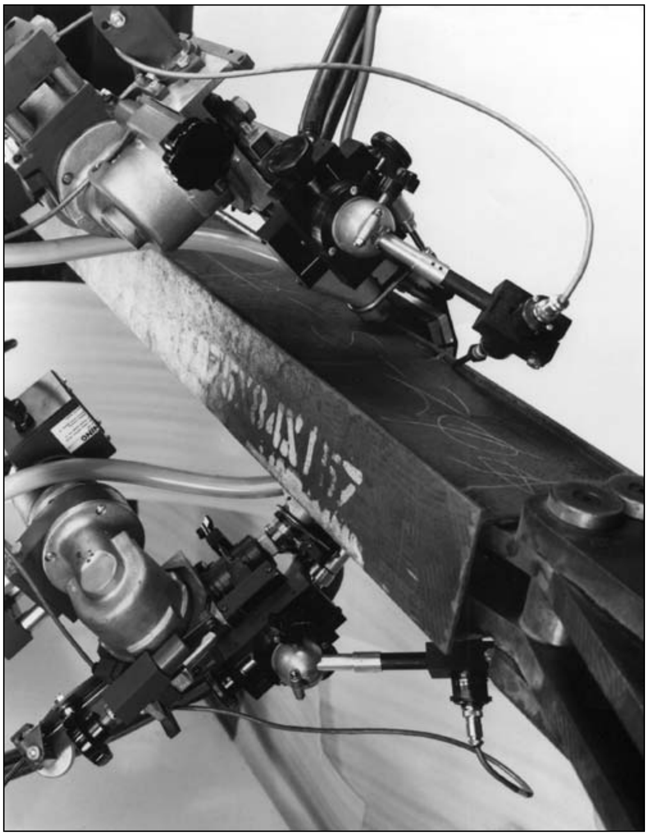
Other sensing techniques have also been investigated for joint finding. These include inductive and capacitive proximity sensing and laser range finding. These sensors allow a noncontact measurement of the torch position with respect to the weldment.

Joint Tracking. As mentioned above, variations in workpiece dimensions, edge preparation, fitup, and distortion can affect the location and size of weld joints. Adjustment of the trajectory of the welding torch relative to the weldment may be necessary as the torch proceeds along the joint. Feedforward joint tracking control is achieved by adjusting the torch's trajectory using an automated manipulator to maintain alignment with the joint in real time during welding. Several methods used for joint tracking are examined below.

Tactile probe sensing utilizes a small mechanical probe or stylus to "feel" the joint with sliding or rolling contact. The probe is aligned with the welding torch. During welding, the movements of the joint relative to the probe cause it to shift it from a null or zero position. Horizontal probe deflections are used for joint tracking, while vertical deflections are used to control torch height. Figure 10.7 presents a commercially available tactile-probe joint tracker.

The tactile probe system is not used for joint searching since the zero or null probe position must be set prior to welding. While this technique is relatively simple and inexpensive, it offers no information on the joint profile or joint area for joint fill control. Although the system can be used with a variety of processes, the probe must contact the workpiece ahead of the torch, which causes access problems for some applications.

Through-arc sensing is another method that is commonly used in joint tracking. This is a noncontact feedback method that relies on detecting changes in arc voltage or current, or both, during gas tungsten arc, gas metal arc, flux cored arc, and submerged arc welding. In this technique, the welding torch is mechanically oscillated from one side of the joint to the other several times per second. The interaction between the arc and the joint sidewalls causes voltage and current changes that are sensed by the welding equipment controller and used for joint edge detection.



Photograph courtesy of Jetline Engineering, Incorporated

Figure 10.7—Tactile Probe Joint Tracking System

The basic theory of operation of the through-arc sensing technique as it is applied in gas metal arc welding is shown in the Figure 10.8. As the arc approaches the joint sidewall, the extension of the electrode decreases, producing changes in the current and voltage. These changes are interpreted by the signal processor as a joint's "edge." The center of the joint can be determined by finding the opposite "edge." This technique is also applicable to flux cored arc and submerged arc welding.

In gas tungsten arc welding, a method similar to that described for arc length control is used for joint tracking. Arc length and arc voltage change as the welding torch is moved toward the sidewall of the joint. The voltage change is again interpreted as an "edge" of a joint.

The advantage of through-arc sensing is that it operates at the point of welding on signals inherent in the welding process. Disadvantages are the need to weave the torch perpendicular to the welding direction and the higher welding heat input that may be needed for weave beads. Through-arc sensing cannot be used for joint searching since the arc must be operating for the technique to work.

Also used to detect joint location, laser-based machine vision systems provide information relating to joint tracking and adaptive fill. Figure 10.9 shows a commercially available laser-based sensor in operation during gas metal arc welding.

These systems are controlled by a computer or microprocessor, which permits multiple joint designs to be recognized. The incorporated sensor is programmed to locate different joint features such as the top edges of joint preparations and the edges of root openings. Additional features such as joint centroids and joint centerlines can then be calculated from the basic characteristics, and the intersections of line segments can be extracted. One disadvantage of this system is that the sensor must be mounted near the welding torch, where it may interfere with joint access.

Other sensing techniques that have been applied to joint tracking include ultrasonic, thermal, and inductive sensing as well as gray-scale machine vision. While these techniques offer advantages for particular applications, they have not become widely available.

Adaptive Fill Control. Adaptive joint fill control systems compensate for changes in the volume of groove welds and for variations in the root openings of fillet-welded joints. These changes in joint volume may be caused by variations in workpiece dimensions, edge preparation, fitup, and distortion during welding. Adaptive joint fill control can be controlled in real time during the execution of the welding process or accomplished by scanning the joint prior to welding.

Weld joint dimensions are measured with devices such as the laser-based structured-light machine vision sensor. The vision system measures the joint dimensions and volume, and the system determines the changes that are needed in the welding variables to compensate for changes in the joint. The control system then initiates the necessary modifications in the welding process variables, such as travel speed, wire feed speed, or both to adjust the volume of deposited weld metal.

Through-arc sensing can also be used for adaptive fill control. Applications extract information from the welding current signal to show the variation in root opening or joint width. This data can be used by the control to modify the weave width, travel speed, or welding current to compensate for the variation in the weld joint.

Other fill controls use the methods discussed under the section titled "Joint Finding" in this chapter inasmuch as any method used for weld seam location can also be used to map out the size and shape of the seam weld by scanning the joint prior to welding. Once the

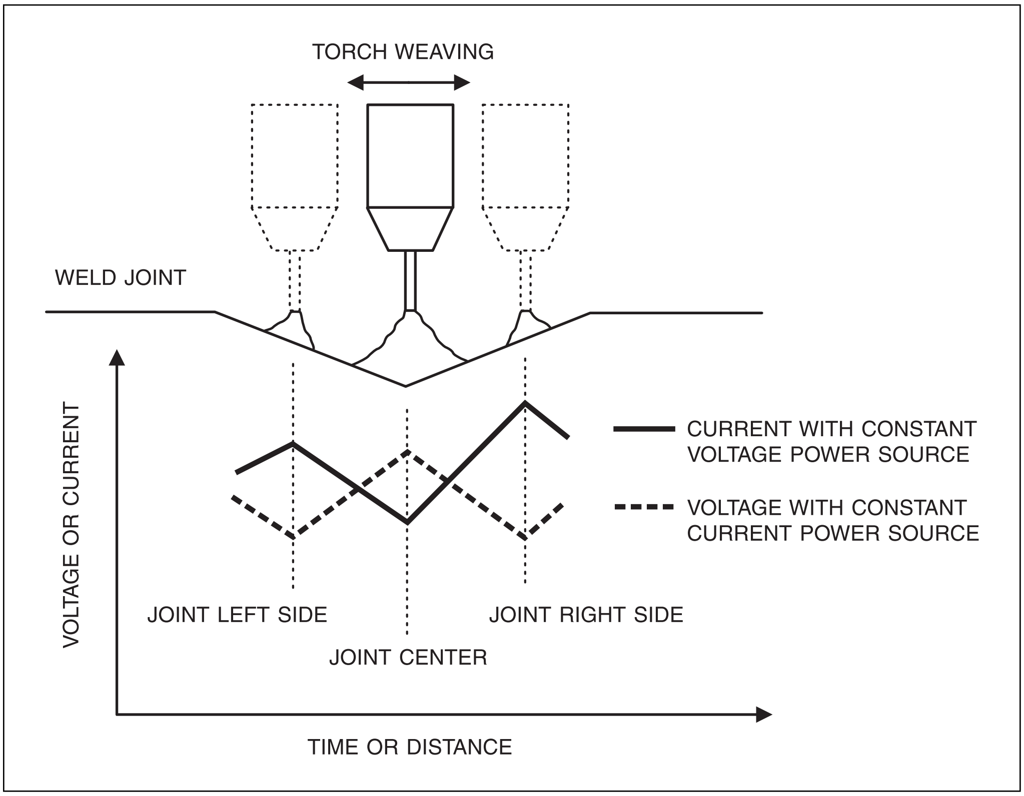


Figure 10.8—Through-Arc Sensing of Joint Tracking

joint is scanned and the size and shape in known, the welding schedule can be selected to fill the weld seam adequately. The disadvantage of these methods is that they do not compensate for disturbances such as thermally induced distortion, which may occur during welding.

Metal Transfer Mode Control. Maintaining the desired mode of metal transfer—whether it be short-circuit, globular, or spray metal transfer—is important for the proper control of arc welding processes such as gas metal arc welding. The metal transfer mode has a significant influence on spatter, penetration, weld geometry, and the presence of discontinuities such as undercut and lack of fusion. Process disturbances, such as variations in contact-tip-to-work distance due to fit-up variations, can cause the transfer mode to change. Control of the metal transfer mode can be achieved by sensing the transfer mode and adjusting the welding parameters to maintain the desired mode.

Through-arc sensing of transfer mode has been investigated for metal transfer control. Both welding current and arc voltage fluctuate during droplet formation, detachment, and transfer to the weld pool. The frequency of droplet transfer and thus an indirect measurement of droplet size can also be determined through the frequency of fluctuations of voltage and current. Frequencies on the order of a few hertz (Hz) indicate short-circuiting and globular transfer modes, while frequencies on the order of hundreds of hertz indicate spray transfer mode.

Arc-light sensing and arc-sound sensing (see above) are also employed to detect transfer mode. While these techniques lack the ability to identify the various stages of transfer, they can determine the frequency of transfer. Through-arc, arc-light, and arc-sound sensing have also been applied to the detection of metal transfer in other arc welding processes, such as flux cored arc welding.

Advancements in computer-controlled welding power sources increase the likelihood of additional transfer mode control through control of welding current and voltage waveforms. Short-circuit control for gas metal arc welding using 100% carbon dioxide shielding gas is one application in which feedback control has been successful. The current and voltage signals are sensed in the power source and short circuit events

Photograph courtesy of Servo-Robot, Incorporated

Figure 10.9—Robotic Welding Application Using a Laser-Based Vision System

are detected. The process parameters are then adjusted in real time to add stability to the process. Waveform control can also be applied to increase the stability of the spray transfer mode for the gas metal arc welding process.

Weld Penetration Control. Penetration is an important weld characteristic because it affects weld size and the load-carrying area of the weld, both of which ultimately influence the structural integrity of the weldment. Inadequate penetration is a weld discontinuity that is to be avoided. Excessive penetration may also be detrimental. The measure and control of weld penetration ensures that sufficient melting and root reinforcement are achieved and that excessive melt-through is prevented.

The majority of effort with respect to penetration control has focused on gas tungsten arc welding rather than on the consumable electrode processes. Consumable processes such as gas metal arc welding, flux cored arc welding, and submerged arc welding are characterized by complex relationships between heat input and weld deposit volume that are difficult to control.

A number of techniques have been applied to penetration control in gas tungsten arc welding. The backside light sensing and ultrasonic sensing methods provide a direct measure of penetration. Machine vision sensing, weld-pool-sag sensing, and weld-pool-oscillation sensing obtain information about the size, shape, and depth of the weld pool to determine penetration. Thermal sensing and acoustic emission sensors relate penetration to temperature distribution or acoustic emission from the weld. The penetration control system uses sensor input to determine when penetration deviates from the desired value. In gas tungsten arc welding, the control of penetration is achieved by adjusting the heat input, which is usually effected by changing the welding current or the travel speed.

Thermal Cycle and Cooling Rate Control. During arc welding, the heat input and cooling rate affect the metallurgical structure, mechanical properties, distortion, and residual stress of the weld and the heat-affected zone. Disturbing variables can affect the heat input and cooling rates. These disturbances include (1) changes in joint geometry caused by tack welds, joint volume changes, and distortion; (2) thermal boundary conditions, such as preheat and variable heat sinking caused by joint variations; and (3) changes in the welding arc itself, such as arc power and heat distribution. Feedback control of weld thermal cycles or cooling rates can be achieved by sensing the temperature distribution in the weldment and subsequently adjusting the heat input through changes in the welding current, arc voltage, and travel speed.

Thermal sensing is the only technique applicable to thermal cycle and cooling rate control. Noncontact techniques such as infrared detectors, cameras, and point sensors (e.g., thermopiles or bolometers) have been used to measure temperature distribution around the weld. Contact sensors such as thermocouples, resistive-temperature devices, or thermistors can also be affixed to or slid along the weldment. These sensors determine peak temperatures at a single distance from the centerline of the weld. Multiple point sensors furnish information regarding the thermal cycle and cooling rate.

Weld Geometry Control. Control of the surface contour of a weld is achieved by sensing the geometry of the surface and adjusting the welding variables to achieve the desired profile. Techniques used to sense the shape of the solidified weld bead include machine vision sensing and laser-based structured-light machine vision sensing.

Weld geometry control has also been investigated using machine vision sensing and infrared sensing techniques to measure the shape of the liquid weld pool. These methods determine weld geometry from the length, width, and trailing-edge shape of the weld pool.

Indirect measurements have also been made of the weld bead and shape of the weld pool by sensing primary process variables such as the welding current, arc voltage, and travel speed.

Arc Spectrum Analysis

Spectrography is a light-sensing technique used to measure spectral wavelengths. The analysis of the intensity of selected wavelengths of radiation emitted from welding arcs has been studied as a process control method. Inasmuch as spectrography can identify the presence of elements in the arc atmosphere, this method has been used to measure hydrogen in the arc during the welding of steels that are sensitive to hydrogen-induced cracking. The method has also been used to measure atmospheric contamination of the arc atmosphere during the gas tungsten arc welding of titanium. In addition, arc spectrum analysis has been proposed to measure base metal dilution during weld overlay cladding and to perform joint tracking when welding two dissimilar materials.

RESISTANCE WELDING

The most important process variables to be controlled during resistance welding are weld time, welding current, voltage, electrode force, travel speed, cooling water temperature, and resistance of the weld zone. The displacement of one of the welding electrodes in contact with the workpieces is also commonly sensed, particularly in resistance projection welding. Modern electronic controls provide very accurate control of weld time; consequently, this variable can be treated as a fixed quantity and need not be monitored.

The variables commonly sensed in resistance welding are listed in Table 10.3. Detailed descriptions of these process variables are presented in Chapter 17 of *Welding Processes*,[4] Volume 2 of the *Welding Handbook*, 8th edition.

Table 10.3
Variables Commonly Sensed in Resistance Welding

Variable	Monitor	Control
Current	✓	✓
Voltage	✓	✓
Electrode force	✓	✓
Electrode displacement	✓	✓
Travel speed	✓	✓
Cooling water temperature	✓	✓

Current

The term *welding current* refers specifically to the current that passes through the workpieces being welded. This variable is sensed using devices such as a Rogowski-type toroid coil, a Hall-effect device, or a current shunt. The welding current can be sensed on either the primary or the secondary side of the welding transformer. When sensed on the primary side of the transformer, it is calculated by multiplying the measured value by the transformer turns ratio, which is the ratio of the number of turns in the transformer primary to the number of turns in the transformer secondary. On the secondary side of the transformer, the welding current can be measured directly.

The welding current has a significant effect on weld quality since the heat generated during resistance welding varies as the square of the current. However, it is the welding current density, which is equal to the welding current divided by the area through which it flows, and not just the magnitude of the current, that is the critical factor.

An example of the importance of welding current density is the change in this variable due to the mushrooming of weld electrodes. To compensate for this phenomenon, assembly plants find it necessary to increase spot weld currents by small amounts every few hundred welds to compensate for the increase in electrode contact areas. However, such current stepper programs are very difficult to establish and execute reliably. In addition, manufacturers that perform large-volume projection welding carry out periodic checks on the shapes and sizes of electrodes to keep current density constant.

Secondary Loop Current. Inasmuch as the electrical function of the secondary loop of the welding machine is to conduct the welding current from the transformer to the workpieces, a low resistance and impedance in the secondary loop should be constructed and maintained. The resistance of the loop depends primarily on the quality of the joints between the many conductors that form the loop. Good surface contacts must be ensured between the faying surfaces. In addition, all copper-copper joints in the secondary can be silver-plated to maintain the low resistance of the joints. Silver in the joints minimizes heat generation and oxidation at these locations.

The area of the secondary loop has a large influence on the loop's impedance, particularly when single-phase ac waveforms are used. While carrying out maintenance

4. See Reference 3.

work on a resistance welding machine, it is common practice to ensure that no changes occur in the secondary loop area by means of the use of shorter or longer loop components.

Closed-loop resistance welding controllers are often used in manufacturing environments to generate specified secondary welding currents. These controllers are able to sense fluctuations in incoming power line voltage within specified tolerances and compensate for them. A relationship between the phase-shift firing angle used by the controller and the resulting secondary welding current is established for a given machine and workpiece configuration. This relationship is used to control the process at a desired current value. However, the relationship between the phase-shift firing angle and the secondary welding current is valid only for a fixed value of secondary loop impedance, assuming no changes in the welding machine's primary circuit and the transformer. Oxidation of the joints in the secondary loop and changes in secondary loop area can affect this relationship and introduce uncertainty into the control of welding current.

Closed-loop controllers that sense the welding current in the primary or secondary and compensate in real-time to generate the specified welding current are less prone to uncertainty in current control due to secondary joint oxidation or loop area changes. Even in these cases, it is a good practice to maintain constant secondary resistances and loop areas.

Secondary Loop Resistance and Impedance Sensors. Resistances in the secondary loops of resistance welding machines are very low. Whole loops often measure less than 100 micro-ohms (µΩ), measured from one weld tip to the other through the transformer with the tips open. Weld joint resistances are usually less than 10 µΩ when the joints are not oxidized. Consequently, the resistance of the measuring leads or the contact resistance between the probes and the surfaces being tested cannot be allowed to influence the measurements.

Thus, it is necessary to use bridge-type circuits that compensate for and eliminate the contact and measuring lead resistances. Such devices are commercially available. It is good practice to check their calibration with a 100 µΩ shunt before every use. While checking the secondary resistances of three-phase dc resistance welding machines with diodes in the secondary loops, the resistance of the loop from one weld tip to the diode pack and from the other side of the diode pack to the other weld tip must be measured and kept low.

Commercially available impedance meters check the impedance of the secondary loops of resistance welding machines. Many manufacturers also have algorithms that readily calculate the impedance of a loop of a given size constructed with conductors of a known cross section. These algorithms are commonly used while sizing welding machine transformers for a given application.

Figure 10.10 shows a micro-ohm meter with long cables that can be used to measure resistance in the secondary circuit of a resistance welding machine. The meter is designed to cancel out the cable and contact resistances from the measured value. This type of meter is necessary since the resistance values are measured in micro-ohms, and the ohmmeters commonly used by electricians provide inaccurate values.

Voltage

Efforts have been made to measure and control the voltage at or near the welding electrodes to keep the welding process stable. Constant secondary voltages result in nearly constant secondary current densities. Such secondary voltage control, if implemented effectively, helps reduce the effects of variables such as electrode mushrooming and workpiece surface conditions, among others.

However, secondary voltages are typically of the order of a few volts, and they are sometimes even less than a volt. Their accurate measurement is further complicated by the voltages induced in the voltage pick-up leads by the strong magnetic fields around the secondary loops of the resistance welding machine. Many different algorithms and mathematical approaches have been attempted to obtain accurate secondary voltage measurements and subsequent closed-loop process control, but few have found commercial applications.

Figure 10.10—Micro-Ohm Meter with Long Cables and Calibration Shunt to Measure Secondary Resistances

Electrode Force

When a resistance spot weld is made, three sources of resistance to the current flow in the weld area occur: (1) the resistance of the electrode to the metal ($R_{e\text{-}m}$), (2) the temperature-dependent bulk resistance of the weldment (R_{b1}, R_{b2}, and so forth), and (3) the resistance of the faying surface (R_{fs}). Among these, R_{fs}, while being a high value before the passage of weld current, reduces to a small value within the first few cycles of welding current flow. Consequently, the main resistances to current flow for longer duration welds are $R_{e\text{-}m}$ and R_{b1}, R_{b2}, and so forth. The applied force influences the R_{fs} and $R_{e\text{-}m}$ during welding as well as the conduction of heat into the electrode(s). The importance of $R_{e\text{-}m}$ in resistance spot welding is not commonly recognized. In fact, a large part of the total heat is generated at the two electrode-to-metal interfaces. For this reason, any process parameter that influences $R_{e\text{-}m}$ is critical.

The electrode force has a very strong influence on the amount of heat generated at the faying surface (weld interface) in short-cycle-time welds and the initial few cycles of a long-cycle-time weld. It also strongly affects the amount of heat generated at the electrode-to-metal interfaces regardless of weld time. Typically, lower electrode forces result in higher electrode-to-metal interface resistances and, as a consequence, an increase in the amount of heat generated during welding. While faying surface resistances are very high before the passage of weld current, they typically decrease to very small values within a cycle or two of weld time. Thus, the effect of electrode force on the amount of heat generated at the faying surface is significant only if the weld time is short, that is, on the order of a few cycles.

Due to the strong effect of electrode force on the heat generated at the faying surface (for short weld times) and the electrode-to-metal interface, occurrences of surface indentation, weld flash, and surface heat effects are reduced by higher electrode forces. If the electrode face is in the form of a radius, greater force increases the effective contact area and reduces the current density. Thus, an increase in electrode force decreases the heat generated.

In projection welding (PW), the rate of burndown of the projection and weld metal expulsion at the faying surface are influenced by the combination of workpiece fitup, welding current, time, and force. It is necessary for the electrode(s) to follow through with the programmed electrode force as the projection burns down. The amount of friction and inertia in the force application system should be small enough to permit effective follow-through of the weld head as the projection burns down to make the weld. As a rule, higher electrode forces result in increased electrode life. As a result, electrode force may help address variations in workpiece fitup.

Welding Electrode Sensors. Both hand-held and permanently installed sensors are used to measure the force applied by the welding electrodes on the weldment. Hand-held force sensors with analog or digital output are commonly used. Analog sensors are also sometimes used to measure welding force since these are less expensive. Digital sensors are preferred since they retain the information for some time and can communicate with other devices.

Most resistance welding controllers have a "Weld/No Weld" switch, which permits the welding machine to be cycled without passing welding current. Most force sensors in the market require the welding current to be turned off to permit force measurement. However, some sensors permit force measurement while passing welding current of tens of thousands of amperes through the sensor. The sensor shown in Figure 10.11 is designed to permit the flow of welding current through the sensor.

Force sensors and load cells can be installed permanently in the welding machine. Typical locations where load cells are mounted include (1) the cylinder ram that pushes the upper conductor down and applies the welding force and (2) the lower welding fixture. In both cases, the load cell is electrically insulated from the secondary circuit and calibrated using a sensor placed between the electrode tips.

Photograph courtesy of Sensotec

Figure 10.11—Sensor Commonly Used to Measure the Force between Welding Electrodes

Devices in which a force sensor is placed inside the electrode tip holder are also available. The water circulating through the electrode tip deflector tube cools the sensor as well as the electrode tip. These devices must be calibrated using the welding force measured at the electrode tip. In addition, an issue that must be addressed with all machine-mounted sensors and load cells is the minimization of voltages induced in the voltage leads of the sensors by the magnetic fields in the secondary of the welding circuit.

Air pressures being fed into the cylinders of the welding machine are commonly monitored and controlled in a manufacturing environment. Pressure switches that ensure that a set pressure is achieved at a specified location in the air hose feeding the cylinder are often used to prevent the premature flow of welding current before the welding force reaches a given value.

Systems that carry out closed-loop control of air pressures very near the cylinder air inlet are commercially available. These are commonly used in combination with piloted air valves and quick exhaust systems to provide real-time pressure control.

These systems also detect leaks in the air system. Some commercial systems check air pressure at more than one location to provide real-time monitoring and control of electrode force. Attached sensor electronics communicate with the weld controller to ensure the correct weld pressures before the current flow is initiated.

Welding force measurements at the electrodes are also used to optimize the resistance weld "squeeze time," the time it takes for the welding force to stabilize after the weld operation is commenced. With only squeeze times programmed into the welding controller, the machine is cycled automatically at different programmed squeeze times. The shortest squeeze time after the welding force stabilizes is the appropriate time to use for that welding cylinder pressure. Squeeze times vary a bit with changes in input air pressures to welding cylinders. Commercially available squeeze-time analyzers facilitate the optimization of the squeeze time.

Electrode Cooling

The importance of electrode cooling with respect to weld quality is often underrated. In resistance spot welding (RSW), the removal of surface heat by means of water-cooled electrodes results in the creation of the weld nugget at the weld interface. In addition, the water-cooling of the electrodes has a strong influence on the temperature profiles in the weld. Surface heat removal by water-cooled electrodes also permits the pulsing of weld current in order to weld thick/thin metal combinations and multiple sheet stackups.

Regarding weld quality in high-volume spot welding, the importance of maintaining electrode tip shape via water-cooling cannot be overemphasized. Failures of welding transformers and phase-shift current control devices (SCRs) are often attributable to insufficient water-cooling.

Electrode tip cooling is monitored in a number of ways. Methods range from monitoring water pressure drops in every water-cooling hose in the welding machine to installing flow rate measuring devices in the resistance welding machine at several locations. Manufacturers often install simple bulbs with colorful rotating spheres inside them to indicate water flow. While this method is effective, it is not quantitative.

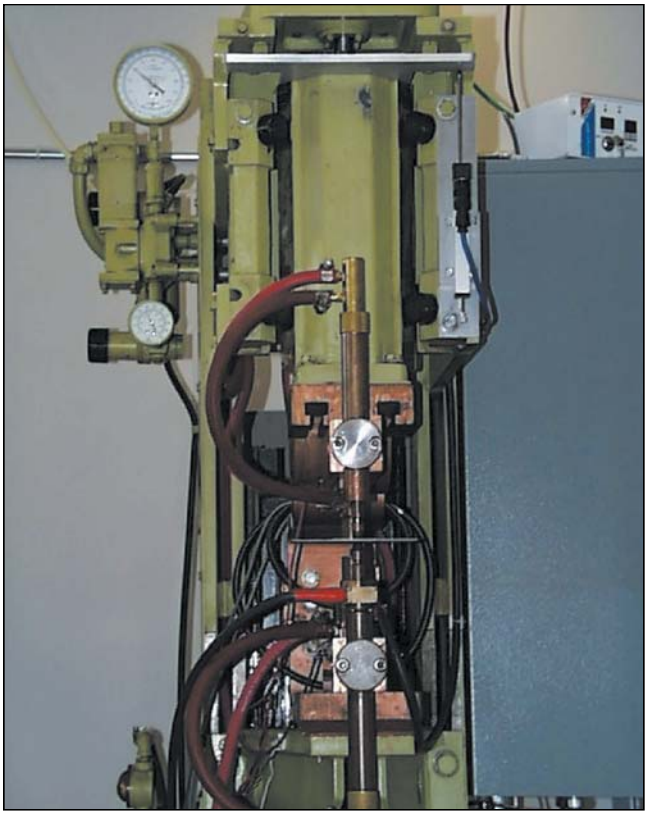
Most large-volume manufacturers also filter the water circulating through the welding machine. Bag-type filters are installed at the main pump and the welders to separate particulate matter. Incoming water pressures and pressure differentials are managed in small groups of welding machines by installing local smaller-sized pumps with water pressure sensors at the farthest distances from the pump.

Care must be taken while measuring and documenting water flow rates by opening a hose and collecting water for a given amount of time. Water drain plumbing in factories is often routed over walls and roofs; thus, the water is forced to follow an upward path before draining. In these cases, the hydrostatic pressure from the drain must be known and accounted for when documenting water flow rates.

Electrode Displacement

Electrode displacement is sometimes monitored during resistance welding. The reasons for taking this measurement vary from application to application. The thickness of the workpieces is sometimes measured to verify that the correct parts are being welded. This practice is particularly useful when frequent changeovers are employed to weld a number of different workpiece combinations. Another technique involves the use a carefully developed correlation between electrode displacement during welding and weld size and strength.

In projection welding, displacement measurements are performed to monitor and ensure weld quality and to monitor the burndown of the projection as well as friction in the welding cylinder. Displacement is also monitored to optimize solidification time (hold time with electrode force maintained) for the weld nugget. Figure 10.12 shows a displacement sensor mounted on a resistance welding machine. This sensor is used to monitor electrode displacement during welding to ensure the correct projection burndown and that the correct electrode and workpiece combinations are being welded.



Photograph courtesy of Sensotec

Figure 10.12—Resistance Welding Machine with Mounted Electrode Displacement Sensor

LASER BEAM WELDING

For laser beam welding (LBW), most of the variables of interest are related to the characteristics of energy transfer from the laser beam to the workpiece. These include optical power, beam mode, beam-material interactions, pulse parameters, focal position, and travel speed. Table 10.4 presents an overview of the laser welding process variables that are monitored and controlled. Laser beam welding parameters are described in more detail in *Welding Processes*,[5] Volume 2 of the *Welding Handbook*, 8th edition.

Beam-Material Interactions Monitoring

Various techniques have been developed to monitor the beam-material interaction that occurs during welding, drilling, and surface modification operations. These techniques rely on the measurement of infrared, ultraviolet, or acoustic emissions created by the plasma plume, weld pool, or parent metal.

Table 10.4
Variables Commonly Sensed in Laser Beam Welding

Variable	Monitor	Control
Optical power	✓	✓
Beam-material interaction	✓	✓
Beam mode	✓	✓
Pulse parameters	✓	✓
Time	✓	✓
Travel speed	✓	✓
Temperature	✓	
Shielding gas flow	✓	
Focal position	✓	✓

Beam Mode Monitoring

Monitoring of the beam mode is used primarily with carbon dioxide (CO_2) lasers to obtain a qualitative determination of the distribution of energy across the laser beam diameter, thus providing a relative indication of system performance. Mode imaging can detect variations in energy distribution, beam diameter, misalignment of beam delivery, beam expander adjustment, and mode burn limitations.

Spatial characteristics—the intensity at various positions within the cross section of the beam—can be obtained using a sweeping wire, hollow needle, rotating drum, or spatial detector array. Several quantitative beam analysis techniques can be employed in the optical train to evaluate the spatial characteristics of a laser beam. Feedback control of laser power and beam quality can be achieved using the same sensors that are employed to monitor beam power and spatial characteristics.

Focus Position Control

In laser beam welding, focus control maintains the distance from the focusing element to the workpiece to provide the proper beam power density at the workpiece. The mechanical techniques developed for maintaining torch-to-work distance in arc welding have been successfully applied in laser beam welding processing. These include tactile, magnetic, and capacitive probes.

5. See Reference 3.

Penetration Control

Acoustic emission has been used to monitor the extent of weld penetration in laser beam welding. The thermal stress formed in materials during welding generates acoustic emissions that travel throughout the workpiece. Thus, the amount of acoustic emission is a function of the amount of fused metal.

In one implementation, a stationary acoustic transducer is mounted in contact with the workpiece. As penetration progresses from partial to full, the frequency content and shape of the acoustic emission change. Another technique is aimed at relating the frequency content and amplitude shape of the emissions to weld penetration.

Thermal Control

Thermal effects during laser beam welding affect mechanical properties, distortion, and residual stress. Feedback control of cooling rates can be achieved by sensing the temperature distribution in the weldment and modifying the heat input by adjusting the laser power and travel speed. Most of the thermal sensors described above can be utilized for the thermal control of laser beam welding. It should be noted, however, that the sensors used for laser beam welding must accommodate the higher speeds and smaller heated zones achieved by this process as compared to the arc welding processes.

Joint Finding and Tracking

As with the mechanized and automated arc welding processes, laser beam welding can benefit from joint finding and joint tracking. Most of the techniques developed for arc welding can be applied to laser beam welding, including laser-based machine, gray-scale machine vision, thermal sensing, and inductive sensing. However, laser beam welding may require increased sensitivity of these techniques in order to provide the proper resolution.

ELECTRON BEAM WELDING

This section describes the methods and means commonly employed to monitor and control the electron beam welding (EBW) process. The techniques outlined below greatly contribute to electron beam welding's capacity to provide an extremely stable method of producing weldments of consistent quality.

Monitoring Systems

Data collected from devices employed to monitor electron beam welding can be used to provide weld quality verification, statistical process control, weld parameter development, and equipment maintenance scheduling. Table 10.5 lists a number of process variables that can readily be monitored and controlled in order to provide the process a high degree of functional stability.

Control Systems

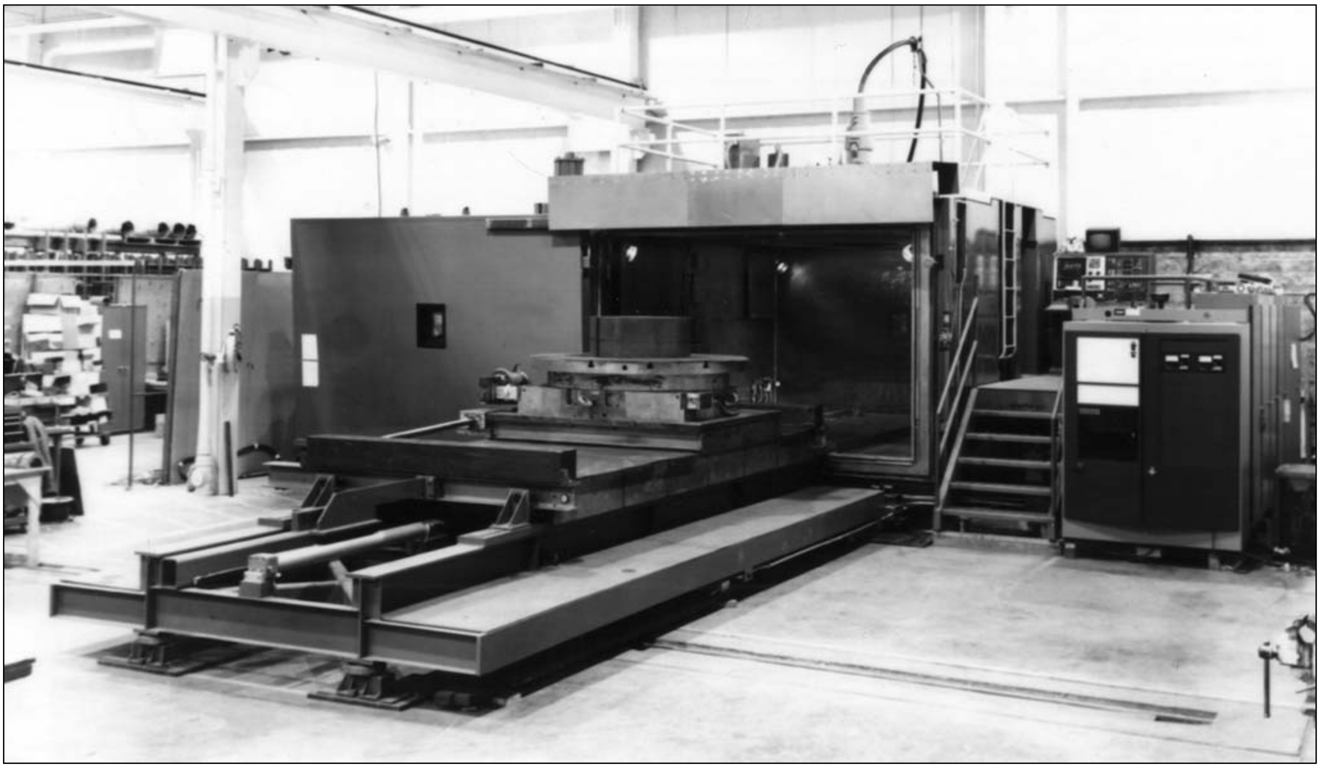
First commercially employed during the late 1950s, electron beam welding is a fast, accurate, and highly reliable fusion joining method. When initially introduced, this process not only had to be performed under high vacuum conditions, but it was also limited to a maximum beam power output capability of 1 to 2 kilowatts (kW). The continued development of electron beam welding technology has resulted in the present-day capability to deliver up to 100 kW of beam power to workpieces located inside or outside a vacuum environment.

The continuing enhancement of electron beam welding process controls has simultaneously increased the process' capability to adapt easily to a wide range of workpiece conditions and operating environments. Beam voltage and current regulation, fast-response beam current level control, real-time seam tracking, versatile beam-deflection capability, computer-integrated workpiece motion, process operational control, process variable monitoring, data logging, and malfunction detection capability are just a few examples of process monitoring and control flexibility that is readily available for use with electron beam welding equipment.

Figure 10.13 shows an electron beam welding system that produces welds approximately 5 inches (in.) (125 millimeters [mm]) deep. This system illustrates the application of many of these process control capabilities. It has the capacity to provide up to 60 kW of continuous beam power and to function totally under the guidance of a computer numerical control (CNC) controller. This controller utilizes software that ensures that all system operations (e.g., workpiece motion, vac-

Table 10.5
Variables Commonly Sensed in Electron Beam Welding

Variable	Monitor	Control
Beam voltage	✓	✓
Beam current	✓	✓
Beam focus	✓	✓
Beam deflection	✓	✓
Beam pulsation	✓	✓
Time	✓	✓
Travel speed	✓	✓



Photograph courtesy of PTR—Precision Technologies

Figure 10.13—Large-Chamber High Vacuum Electron Beam Welding System

uum sequencing, beam generation, and so on) can be performed in either a manual or fully automatic manner. The system also oversees all variable settings, seam tracking, and data logging functions.

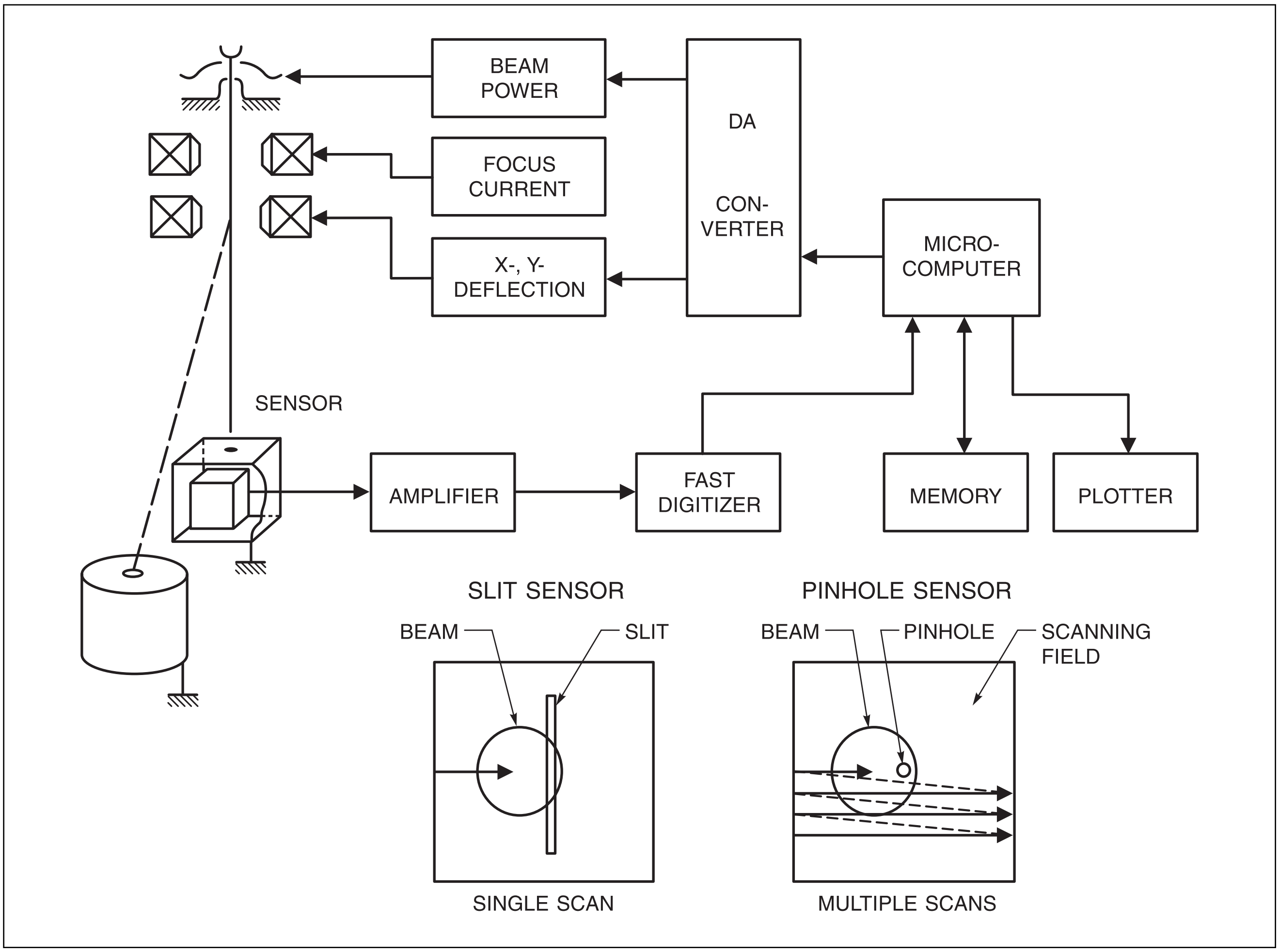
Modern electron beam welding units also have beam diagnostic devices that allow the geometric characteristics of the electron beam to be readily quantified. This provides the user a tool to ensure the repeatability of weld quality. These diagnostic devices sweep the beam rapidly and repeatedly across a sensor that is coupled to a computer at scan speeds that prevent the sensor from incurring any damage. A schematic of a typical diagnostic system is shown in Figure 10.14.

The computer can quickly calculate and plot beam energy density profile graphs. These graphs can be used to verify that the beam's geometrical characteristics have not changed with the passage of time. Figure 10.15 uses this capacity to illustrate the effect produced on the energy density distribution of a 150 kilovolt (kV)/20 milliampere (mA) electron beam sharply focused in a plane at a work distance (W. D.) of 14 in. (350 mm) when the beam focus setting is varied slightly above and below the optimal focus value for this particular work distance.

Variable-frequency programmable pattern generator deflection devices are commonly employed to permit the beam to be scanned over a workpiece without destroying it. These devices can be used to deliver energy to the workpiece in both a discrete and continuous fashion in a precisely described manner.

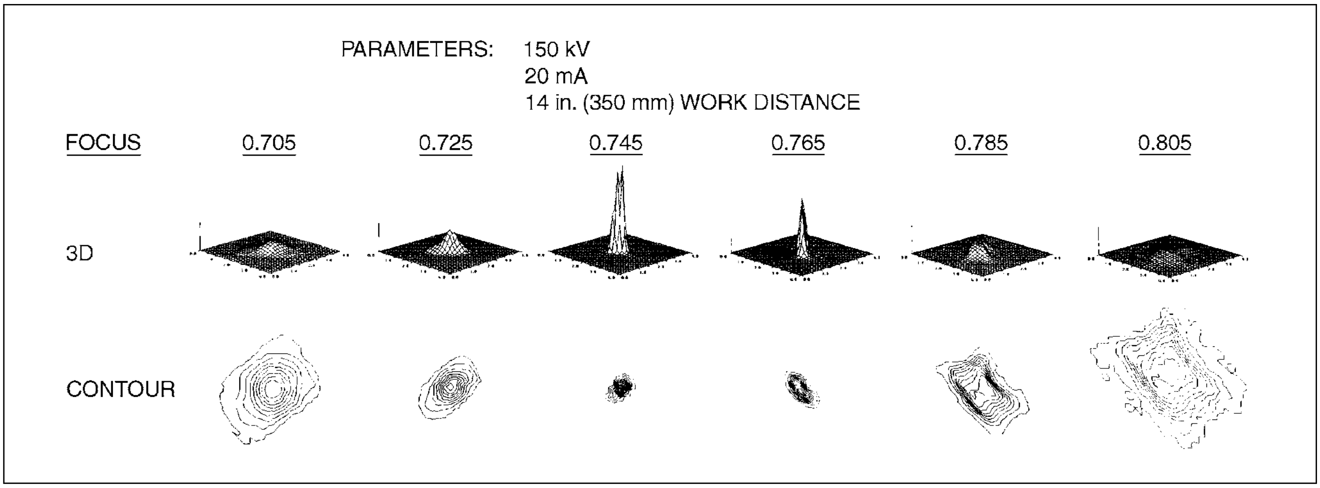
Figure 10.16 shows a sampling of various styles of beam deflection patterns achievable with a modern pattern generator. It also illustrates the types of cosmetic surface effects that can be produced when these particular patterns are superimposed onto a weld motion. In addition to providing a cosmetic surface effect, cyclic beam motion can also be employed during welding to provide a weld puddle stirring motion, which results in improved weld quality.

The capacity for real-time seam tracking can also be accomplished by scanning the joint seam ahead of the weld with the electron beam. This combination of static and dynamic beam deflection produces a signal that the control unit can use to compensate automatically for any beam-to-seam misalignment that might result from seam runout or stray magnetic fields.



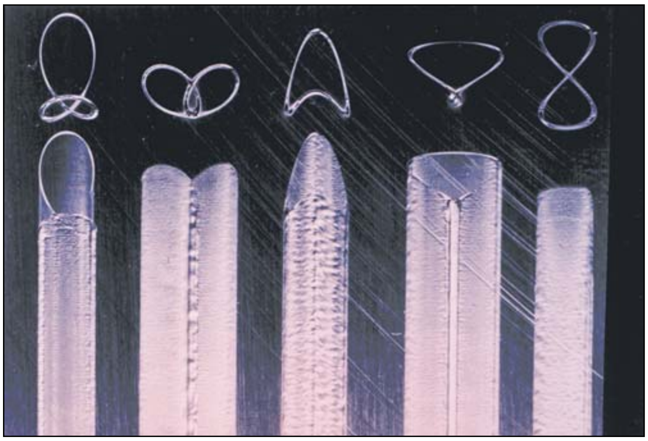
Courtesy of PTR—Precision Technologies

Figure 10.14—Electron Beam Diagnostic System Schematic and Aperture Types for the Sensor Unit



Photograph courtesy of PTR—Precision Technologies

Figure 10.15—Energy Density Distributions at Different Focus Settings for Electron Beam Welding



Photograph courtesy of PTR—Precision Technologies

Figure 10.16—Examples of Electron Beam Deflection Patterns and Typical Effects on the Workpiece

Figure 10.17 schematically defines the manner in which a secondary electron emission sensing (SEES) system operates for joint tracking. Most electron beam equipment also allows "beam's eye" viewing of the workpiece through a high-resolution, closed-circuit color television viewing system, as shown in Figure 10.18.

Concurrent with providing real-time seam tracking and misalignment correction capability, the CNC unit controls the following "axes" in a continuous interpolating fashion:

1. Linear movements of the workpiece,
2. Rotary movements of the workpiece,
3. Beam current,
4. Beam deflection amplitudes,
5. Beam deflection frequencies, and
6. Beam focus.

The CNC controller also provides continuous monitoring of the programmed operational commands. An appropriate error message like that shown in Figure 10.19 indicates detected functional faults.

Modern electron beam welding systems normally employ high-frequency (switch-mode style) power supplies instead of the low-frequency (transformer-style) power supplies and the primary steering (motor generator [MG] or silicone control rectifier [SCR] variety) units that were previously employed. The switch-mode units prevent uncontrolled "arc outs" from occurring by sensing an impending condition and reducing the high voltage until the arc is quenched before automatically returning the high voltage to the proper operating level. These switch-mode power supplies utilize a high-frequency generator source (usually greater than 20 kHz) that provides both a source of very low stored energy and the solid-state switching electronics needed to allow the beam current and voltage to be monitored continuously. In this way, impending arc outages can be sensed and easily controlled.

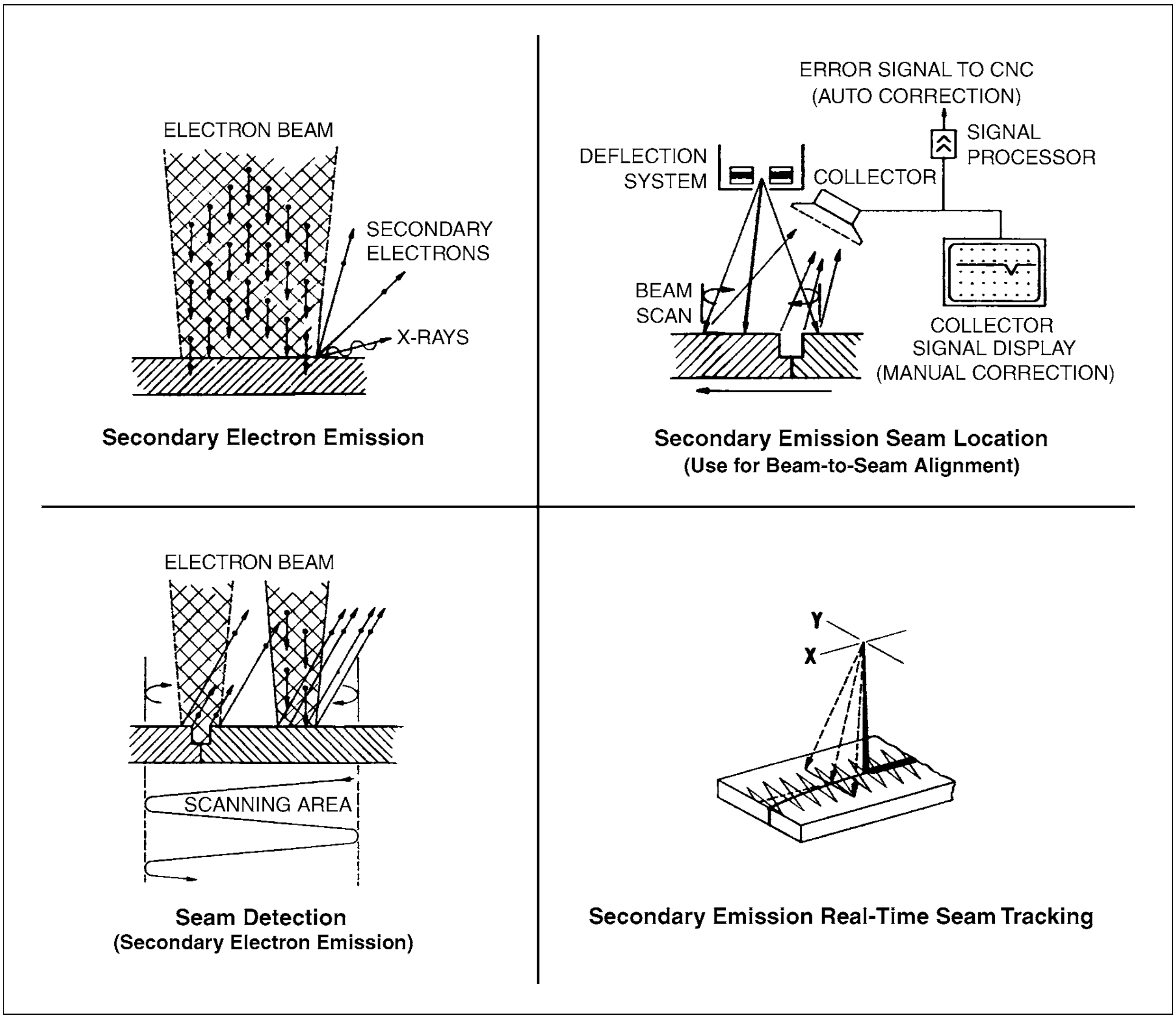
FRICTION WELDING

Friction welding (FW) is a solid-state process that uses heat and compressive force to produce a weld. The heat is produced by friction as one of the workpieces rotates or slides against the other. The force is applied to maintain contact between the workpieces during the heating and forging portions of the welding cycle. The relative motion between the workpieces can be rotary, linear, or orbital in nature. This motion determines whether the process is known by one of several descriptive names, including *direct-drive friction welding*, *inertia friction welding*, *radial friction welding*, *orbital friction welding*, *linear friction welding*, *friction surfacing*, *friction stir welding*, and *friction hydro-pillar processing*.

Friction welding is a machine welding process in which the welding variables are set prior to welding. Normally, the machine operator's function is to load and unload the parts from the machine. Fully automated friction welding operations also are common. Table 10.6 lists the friction welding variables that are commonly monitored and controlled.

Process monitors for friction welding consist of sensors that observe process variables and computers or programmable logic controllers that compare sensor inputs to preset values. When the sensed variables exceed preset values, these monitors sound an alarm or shut down the machine. In addition, process monitors can provide a permanent record of variables for each weld, thus supplying data that can be used for statistical process control. Sensor input can be used for process control as well.

Process monitoring is most widely applied to direct-drive and inertia welding inasmuch as these are the most common friction welding processes in industrial use. Three primary variables control the quality of direct-drive friction welds—rotational speed, axial force, and time. Force and time are monitored and controlled for individual portions of the weld cycle, including the friction, upset, and postweld cycles. The process can be controlled by applying force for a preset time or by measuring the displacement of the workpiece and controlling the friction and upset cycles to achieve a predetermined upset distance. Inertia friction welding involves three process variables—initial rotational



Courtesy of PTR—Precision Technologies

Figure 10.17—Principles of Secondary Electron Emission Sensing (SEES) for Seam Tracking in Electron Beam Welding

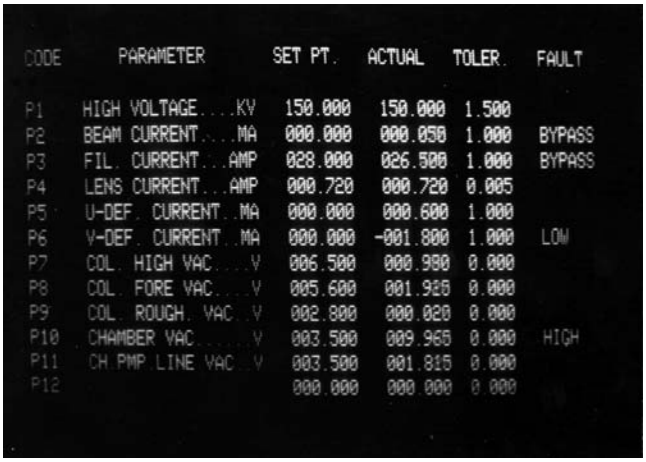
speed, moment of inertia, and axial pressure. Speed and pressure are monitored during inertia friction welding.

Various sensors are used to monitor friction welding. Temperature-compensated pressure transducers are connected to the forge cylinder of the welding machine. These sensors monitor pressure during the friction cycle as well as during the upset and postweld forming stages of the weld cycle. Tachometers are used to measure the rotation speed of the spindle for rotational welding.

Displacement sensors, which are typically composed of a linear variable differential transformer, measure the relative movement of the work carriage of the friction welding machine. This permits measurement of the initial length of the workpiece, which can be compared to maximum and minimum length tolerances. The displacement of the carriage can be measured during the friction and upset cycles. The final length of the workpiece or the total upset length can also be measured and controlled. When rotational displacement is critical on some parts, an angular displacement sensor mounted to the spindle of the machine can measure the precise angular displacement of the shaft relative to a specified angle.

Photograph courtesy of PTR—Precision Technologies

Figure 10.18—Operator's Station with AUTO/Manual Controls and a Television Viewing System for a Large Chamber-Variety Electron Beam Welding Machine



Photograph courtesy of PTR—Precision Technologies

Figure 10.19—CNC Parameter Value Display Screen indicating Fault Detection Warning Capability

Time is the final variable that is monitored and controlled. The time increments of each portion of the welding cycle are monitored and compared to preset limits. The following are typically monitored individually:

1. Time needed for the spindle to reach speed,
2. Time for the friction portion of the cycle,

Table 10.6
Variables Commonly Sensed in Friction Welding

Variable	Monitor	Control
Workpiece speed	✓	✓
Time	✓	✓
Pressure	✓	✓
Force	✓	✓
Displacement	✓	✓
Travel speed	✓	✓
Temperature	✓	✓

3. Time for braking,
4. Upset time,
5. Postweld pressure time, and
6. Total weld cycle time.

In addition to determining that each process variable is within the preset minimum and maximum values, other variables can be calculated from sensor input. These variables include the rate of the acceleration and deceleration of the spindle, the rate of upset, and the rate of pressure buildup. The calculated value can then be compared to the specified value.

BRAZING PROCESSES

Brazing processes join materials with the use of heat and a filler metal that melts at a temperature below the solidus temperature of the base metals being joined. The filler metal flows by means of capillary action between the closely fitting surfaces of the braze joint to form bonds with the base metal. Heat is provided by a number of methods, including fuel-gas torches, gas or electric furnaces, induction coils, electrical resistance, molten flux, and heat lamps.[6]

Brazing specifications and procedures commonly require monitoring and control of the brazing temperature, brazing time, and brazing atmosphere (including vacuum), if used. Furnace, flux bath, and induction procedures require instrumentation to measure, control, and record temperature throughout the brazing

6. American Welding Society (AWS) Committee on Brazing and Soldering, 20XX, *Brazing Handbook,* 5th ed., Miami: American Welding Society; O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

cycle.[7] Temperature measurement and control may involve the temperature of the furnace or flux bath as well as of the parts being brazed. Temperatures are most often measured with thermocouples, although pyrometers, infrared sensors, and other methods can be used.

Controlled atmospheres are commonly used in furnace, induction, and resistance brazing to protect the brazements from oxidation. The controlled atmosphere may be a vacuum or an inert gas such as argon, helium, hydrogen, or nitrogen, or one of several other reducing atmospheres. These atmospheres are monitored to maintain them within the limits established in the brazing procedure.

Instruments are commercially available to measure the dew point as well as the composition of brazing atmospheres. Thermocouple and electronic vacuum gauges are used to monitor the vacuums used for brazing, depending on the pressure levels involved. Oxygen sensors are also used to monitor the quality of inert or other controlled-atmosphere compositions. Further details on the requirements for the instrumentation used in the monitoring of brazing operations are provided in documents referenced in the Bibliography and the Supplementary Reading List.

CONCLUSION

As outlined in this chapter, the use of state-of-the-art monitoring and control techniques has greatly enhanced the overall reproducibility, capability, and quality of a broad range of welding and joining processes.

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7. American Welding Society (AWS) Committee on Brazing and Soldering, 1990a, *Specification for Induction Brazing*, ANSI/AWS C3.5-90, Miami: American Welding Society; American Welding Society (AWS) Committee on Brazing and Soldering, 1990b, *Specification for Furnace Brazing*, ANSI/AWS C3.6-90, Miami: American Welding Society; American Welding Society (AWS) Committee on Brazing and Soldering, 1993, *Specification for Aluminum Brazing*, ANSI/AWS C3.7-93. Miami: American Welding Society; American Welding Society (AWS) Committee on Brazing and Soldering, 1992, *Recommended Practices for Design, Manufacture, and Inspection of Critical Brazed Components*, ANSI/AWS C3.3-92R, Miami: American Welding Society.

8. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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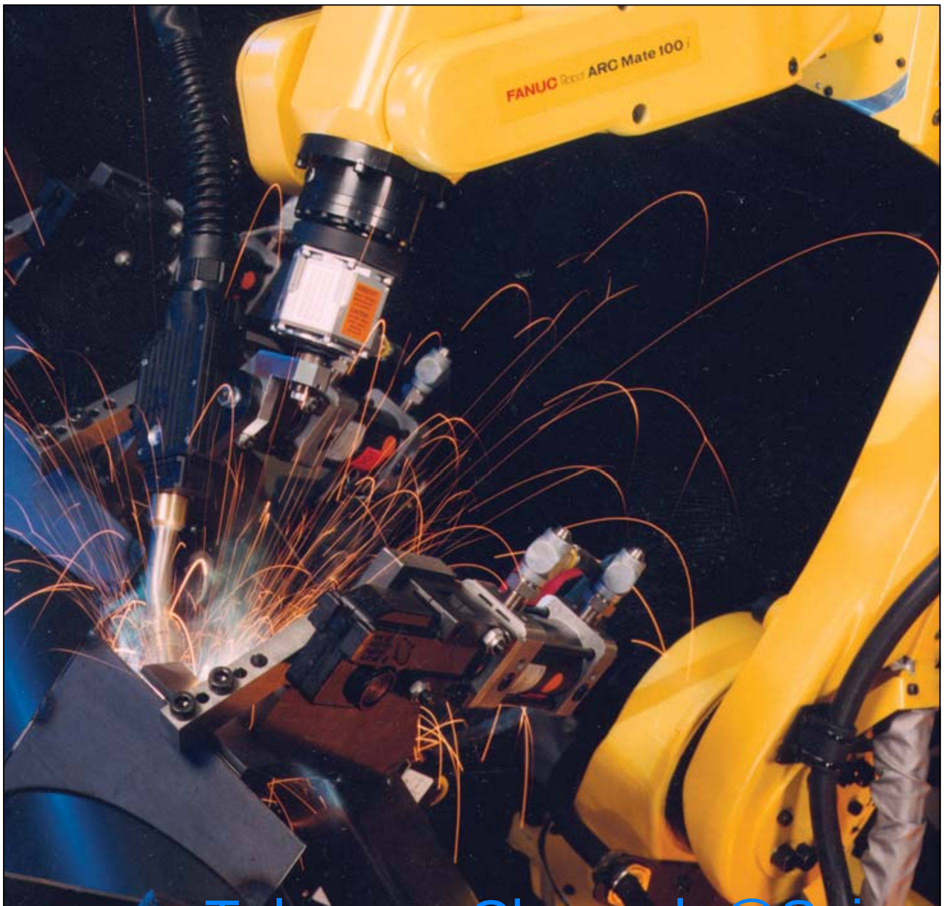
CHAPTER 11

MECHANIZED, AUTOMATED, AND ROBOTIC WELDING



Photograph courtesy of Fanuc, Incorporated

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CHAPTER 11

MECHANIZED, AUTOMATED, AND ROBOTIC WELDING

INTRODUCTION

The methods of applying the various welding processes are categorized according to the degree of operator involvement in the performance of welding operations. In manual welding, defined in the American National Standard *Standard Welding Terms and Definitions*, AWS A3.0:2001, as "welding with a torch, gun, or electrode holder held and manipulated by hand,"[1, 2] the welder performs the welding function and maintains continuous control of the welding operations by hand. In semiautomatic welding, defined as "manual welding with equipment that automatically controls one or more of the welding conditions,"[3] the welder manipulates the welding gun to create the weld while the electrode is automatically fed to the arc.

In mechanized welding, defined as "welding with equipment that requires manual adjustment of the equipment controls in response to visual observation of the welding, with a torch, gun, or electrode holder held by a mechanical device,"[4] the welder's intervention consists of adjusting the equipment controls in response to visual observation of operations.

In automated welding, defined as "welding with equipment that requires only occasional or no observation of the weld, and no manual adjustment of the equipment controls,"[5] the welder's involvement is limited to activating the machine to initiate the welding cycle and observing the weld on an intermittent basis, if at all.

Robotic welding, defined as "welding that is performed and controlled by robotic equipment,"[6] entails no involvement on the part of the welding operator in performing the weld, as the welding operations are carried out and controlled by welding robots.

In both automated and robotic welding, however, the operator plays an active role in quality control through the identification of the presence of weld discontinuities. When discontinuities are encountered, appropriate measures must be taken on the part of maintenance or programming personnel to correct deviations.

Adaptive control welding is defined as "welding with a process control system that automatically determines changes in welding conditions and directs the equipment to take appropriate action."[7] This process application relies on sensors to provide real-time data regarding abnormalities to the computer controller. The controller then makes the necessary changes in welding parameters to produce quality welds. Thus, welding is performed and controlled without operator intervention or supervision.

Figure 11.1 summarizes the capabilities of the different welding application methods.

1. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami, American Welding Society, pp. 50–51.
2. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami, American Welding Society, p. 67.
4. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami, American Welding Society, p. 51.
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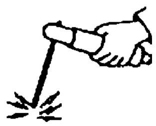
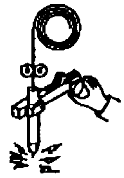
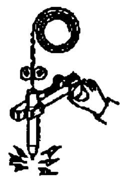
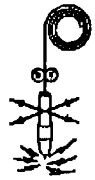
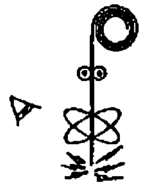
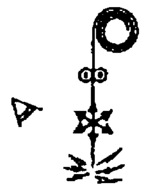
Method of Application	Manual	Semiautomatic	Mechanized	Automatic	Robotic	Adaptive Control
Arc Welding Elements/Function						
Starts and maintains the arc	Person	Machine	Machine	Machine	Machine (with sensor)	Machine (robot)
Feeds the electrode into the arc	Person	Machine	Machine	Machine	Machine	Machine
Controls the heat for proper penetration	Person	Person	Machine	Machine	Machine (with sensor)	Machine (robot) (only with sensor)
Moves the arc along the joint (travels)	Person	Person	Machine	Machine	Machine (with sensor)	Machine (robot)
Guides the arc along the joint	Person	Person	Person	Machine via prearranged path	Machine (with sensor)	Machine (robot) (only with sensor)
Manipulates the torch to direct the arc	Person	Person	Person	Machine	Machine (with sensor)	Machine (robot)
Corrects the arc to overcome deviations	Person	Person	Person	Does not correct; hence, potential weld imperfections	Machine (with sensor)	Machine (robot) (only with sensor)

Source: Adapted with permission from Cary, H. B., 1994, *Modern Welding Technology*, 3rd ed., Englewood Cliffs, New Jersey: Regents/Prentice Hall, Figure 12-1.

Figure 11.1—Methods of Applying Welding Processes

MECHANIZED WELDING

Mechanized welding is often selected and implemented to reduce labor costs and improve quality, especially when performing welding and cutting operations involving large components or structures. It can be used to apply most fusion welding and thermal cutting processes.

In mechanized welding, the welding operation is performed under the observation and control of a welding operator. The mechanized welding equipment controls the following variables:

1. Initiation and control of the welding arc,
2. Feeding the welding electrode wire into the arc, and
3. Control of movement and travel speed along the joint.

The equipment may or may not perform the loading and unloading of the workpieces.

Mechanized welding must allow sufficient time for the welding operator to monitor and control the guidance aspects of the operation as well as the welding process variables. Weld quality and productivity are often enhanced as a result of the proper control of process variables. To perform this task, the operator must be positioned near the point of welding to observe the operation closely. He or she interacts continually with the equipment to ensure the proper placement and quality of the weld metal. Changes to wire feed speed, current, voltage, torch position, torch extension, and travel speed may be required.

The travel speed of the carriage is an important welding variable, as uniform speed and weld direction during operation are vital for quality welds. Quality also depends on how rigidly the welding carriage is held to the track because excessive vibration or dimensional variation can adversely affect the wire tip position.

Mechanized welding improves the efficiency of the process while minimizing operator fatigue, thereby increasing the consistency and quality of the welds. This application method is capable of yielding uniform, consistent weld profiles when producing long linear or circumferential welds. When a change in production requires a new setup, microprocessors are utilized to change preset parameters, reducing the likelihood of human setup errors that may cause lower quality welds and lost production. Mechanized welding requires fewer starts and stops compared to manual welding, thus reducing the probability of various weld discontinuities associated with breaking and restarting the welding arc. A mechanized welding system is shown in Figure 11.2, which depicts a side-beam carriage performing submerged arc welding on structural columns.

SYSTEM COMPONENTS

The system components used in a mechanized welding installation include a power source, gas supply, wire spool holder, feeding mechanisms, tracking system, and travel devices.

Travel Devices

In mechanized welding, various travel devices provide a means for moving an automated welding head relative to the workpiece being welded or vice versa. The workpiece may be stationary while a welding head is moved mechanically along the weld joint, or it may be moved under a stationary welding head. The travel devices employed in mechanized welding operations are generally grouped into the following four categories:

1. Welding carriages,
2. Welding head manipulators,
3. Specialized welding machines, and
4. Welding positioners.

Welding Carriages. Welding carriages provide a relatively inexpensive means for arc motion. A typical carriage rides on a linear or curved track of the same contour as the joint to be welded, as shown in Figure 11.3. For welding in the flat position, some carriages

Photograph courtesy of The Lincoln Electric Company

Figure 11.2—Side-Beam Carriage Guides Two Submerged Arc Welding Heads for the Fabrication of Structural Columns

Photograph courtesy of The Lincoln Electric Company

Figure 11.3—Technician Examines a Side-Beam Carriage with a Submerged Arc Welding Head Used in a Hardfacing Application

are specifically designed to ride on the surface of the material being welded, whereas others use the actual weld joint for guidance.

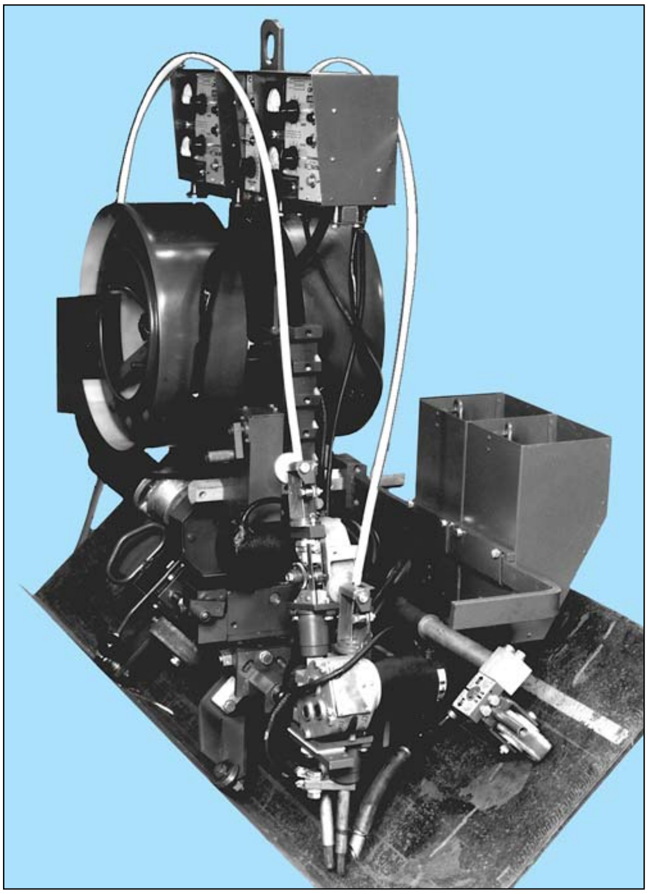
Since the welding carriage is designed to permit the operator to monitor and interact with the system, the carriage and welding controls are typically placed close to the operator. In Figure 11.4, an operator monitors a side-beam carriage with a twin wire feed system performing submerged arc welding on earth-moving equipment.

Tractor carriages weld primarily in the flat or horizontal position. Other types of welding carriages are employed for welding in the horizontal, vertical, or overhead positions. Carriages that are designed to follow irregular joint contours employ a special track or cam upon which the welding carriage is mounted.

A self-propelled welding carriage is shown in Figure 11.5. This welding tractor, which travels along the surface of the workpiece, employs a tandem submerged arc

Photograph courtesy of The Lincoln Electric Company

Figure 11.4—Side-Beam Carriage with a Twin-Wire Submerged Arc Welding System as Used in an Earth-Moving Equipment Application



Photograph courtesy of The Lincoln Electric Company

Figure 11.5—Self-Propelled Mechanized Welding Carriage Employing a Tandem Submerged Arc Process for Large Structural Welds

process, often used to perform the large welds required in structural, bridge, and ship welding.

The side-beam carriage shown in Figure 11.6 is mounted on a horizontal beam and provides powered linear travel for the welding heads. The powered welding carriage supports the welding head, welding wire feeder, and usually the operator control panel. The welding head is adjustable for vertical height and horizontal cross-joint position. The welding operator monitors the operation and adjusts the welding position and travel speed of the side-beam carriage to accommodate different welding procedures and variations in workpiece fitup.

Welding carriages are most productive when used in the fabrication of long, flat-position groove and fillet welds such as those found in ships and barges as well as in cladding applications for improved wear or corrosion resistance. They are also useful in fieldwork, such as in the erection of bridges and the construction of storage tanks.

Welding Head Manipulators. Welding manipulators are used to position the welding head for longitudinal, transverse, and circular welds. Manipulators typically consist of a vertical mast and a horizontal boom that carries an automated welding head. They usually have power to move the boom up and down the mast, and in most units, the mast swivels on the traveling base. In some manipulators, the welding head moves along the boom; in others, the boom moves horizontally on the mast assembly. Most manipulators have controls that move the weld head slowly in the vertical and transverse directions. This movement allows the operator to adjust the position of the welding wire to compensate for variations along the weld joint.

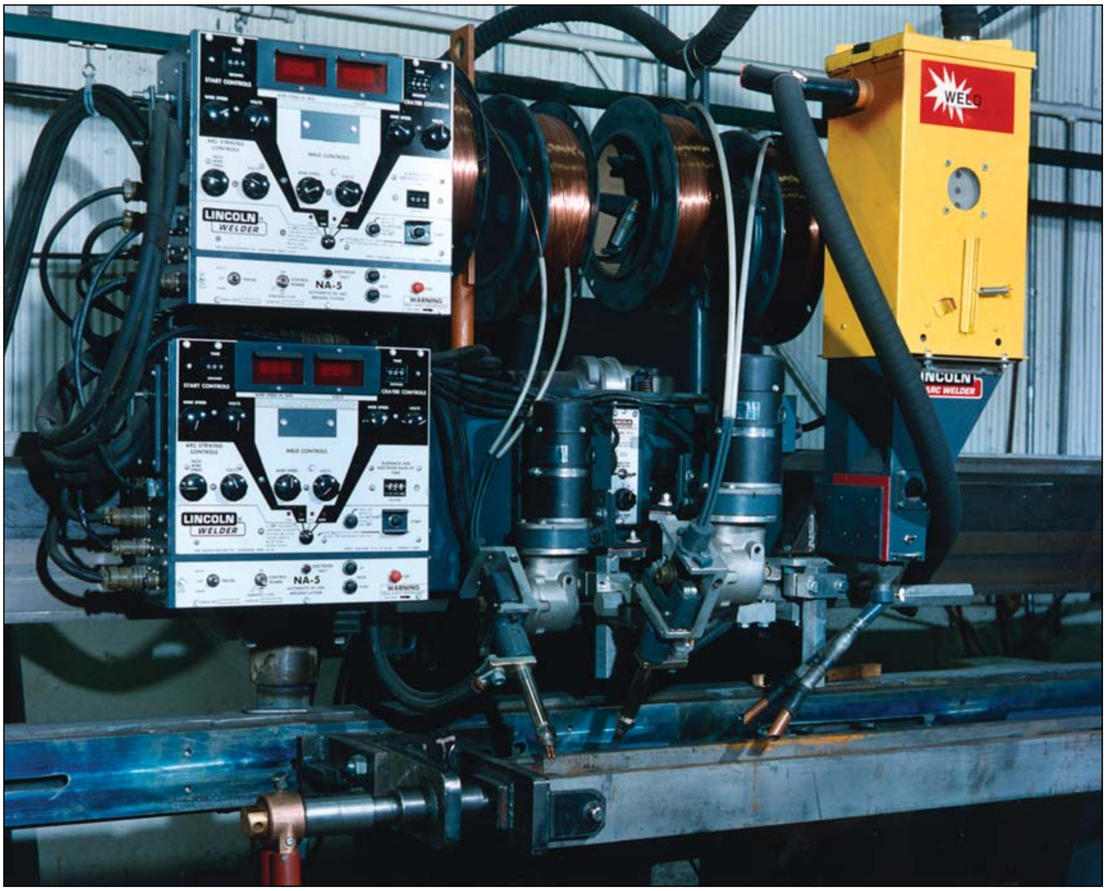
A large welding head manipulator carrying a submerged arc welding unit is shown in Figure 11.7. It can be observed that all welding and manipulating controls are placed at the operator station.

During operation, it is essential that the boom or welding head move at uniform speeds compatible with the welding process. The carriage must move uniformly and at constant speeds if the manipulator is designed to move along tracks on the shop floor. The manipulator must be rigid, and deflection must be minimized to reduce the probability of weld wire mislocation.

In selecting and specifying a welding manipulator, it is important to determine and compensate for the actual weight to be carried at the end of the boom. Heavy-duty manipulators often support the weight of the operator as well as that of the welding equipment.

Specialized Mechanized Welding Machines. Specialized mechanized welding machines have custom clamping devices, workpiece transfer, load and unload systems, torch travel mechanisms, and other special features. Welding machines equipped with orbital heads, for example, are used to make circumferential and longitudinal welds on tanks and cylinders, pipe, and tubing. Other specialized welding machines are used to fabricate flanged beams, weld studs or bosses to plates, and perform special maintenance functions, such as rebuilding track pads for crawler tractors. A special mechanized welding machine that clamps and welds covers on axle housings for light trucks is shown in Figure 11.8.

Welding Positioners. A positioner is a mechanical device that supports and moves a weldment to the desired position for welding and other operations. Motion is controlled by means of servo-controlled motors, pneumatic cylinders or motors, or hydraulics, depending on the weight of the weldment and the



Photograph courtesy of The Lincoln Electric Company

Figure 11.6—Side-Beam Carriage Carrying Submerged Arc Heads That Perform Two Welds Simultaneously on Structural Beam Components

desired accuracy of motion. In some cases, the positioner moves the weldment as welding progresses along a joint. Turntables, turning rolls, and elevating devices are among the various types of weldment positioners.[8]

AUTOMATED WELDING

In manufacturing, the term *automation* denotes that some or all of the functions or steps in an operation are controlled or performed in sequence by mechanical or electronic means. Automation may be partial, with certain functions or steps controlled or performed manually (partial automation or mechanized welding), or it may be full, meaning that all functions and steps are performed by the equipment in a designed sequence with little or no adjustment by the operator (total automation or automated welding). Automation systems may include the automated loading and unloading of the components of the operation.

Automation can be applied to many welding, brazing, soldering, and thermal cutting processes as well as to numerous ancillary operations. Automated equipment can be designed to perform a function on a single assembly or a group of similar assemblies. This type of application is termed *fixed automation.* Alternatively, automated equipment can be configured to modify and adapt itself to perform similar operations on different components or assemblies. This is termed *flexible automation*. Reprogrammable welding robots represent the highest level of flexible automation.

8. For additional information on positioners, see Chapter 9 of this volume.

Photograph courtesy of The Lincoln Electric Company

Figure 11.7—Mechanized Welding Head Manipulator Performing Internal Longitudinal Welds in Tank Fabrication

The objective of an automated system is to reduce manufacturing costs by increasing productivity and improving weld quality. Cost reduction is made possible by reducing or eliminating the redundant manual or semiautomated operations associated with long production runs of identical parts or series of batch runs of similar parts. Automating the welding operation required to fabricate a component often provides the opportunity to perform multiple operations with one dedicated welding system. Other benefits of automation typically include decreased floor space requirements, reduced in-process inventory, and increased throughput. The integration of automation concepts into production scheduling improves productivity, resulting in faster deliveries to customers.

Automation can succeed or fail depending on the application. A successful application requires careful planning; economic justification; and the full cooperation and support of management, product designers, manufacturing engineers, production workers, and maintenance personnel. To determine if automation is feasible, the product, the process to be implemented, the available technology, the availability of a trainable work force, and the total capital outlay for plant equipment must be carefully considered.

Though the introduction of an automated welding system can offer tremendous opportunity for improved productivity and quality, many issues need to be considered when acquiring automated welding equipment and developing automated welding procedures, methods, and production controls. Users—especially those who are new to automated equipment—must address all the issues associated with this equipment at the outset. As these issues impact the equipment's payback period, they should be considered when calculating the justification for the acquisition of automated equipment. These issues include:

1. Operator job classification,
2. Operator skills and training,
3. Production backup capability,
4. Component part repeatability,
5. Repair procedures,
6. Inter-shift communications,
7. Safety procedures,
8. Consumables and spare parts,
9. Test equipment and procedures,
10. Maintenance capability and procedures,
11. Material handling,
12. Calibration of equipment and procedures,
13. Production support personnel, and
14. Quality control requirements, including a quality control plan.

FUNDAMENTALS

Automated welding is performed with equipment that manages an entire welding operation without real-time adjustment of the controls by the welding operator. An automated welding system may or may not perform the loading and unloading of components. Automated welding incorporates the same basic elements of mechanized welding, plus a mechanical or electromechanical device that controls the welding cycle. Continuous weld parameter control, welding arc placement and motion, and workpiece positioning technology are basic to automated welding.

Figure 11.9 depicts a submerged arc welding system with dedicated fixturing used to perform the automated hardfacing of components for earth-moving equipment. The system guides the welding head along the seam while the torch oscillates to produce a wide surface area.

Automated welding requires welding fixtures to hold the workpieces in position with respect to each other.

Photograph courtesy of The Lincoln Electric Company

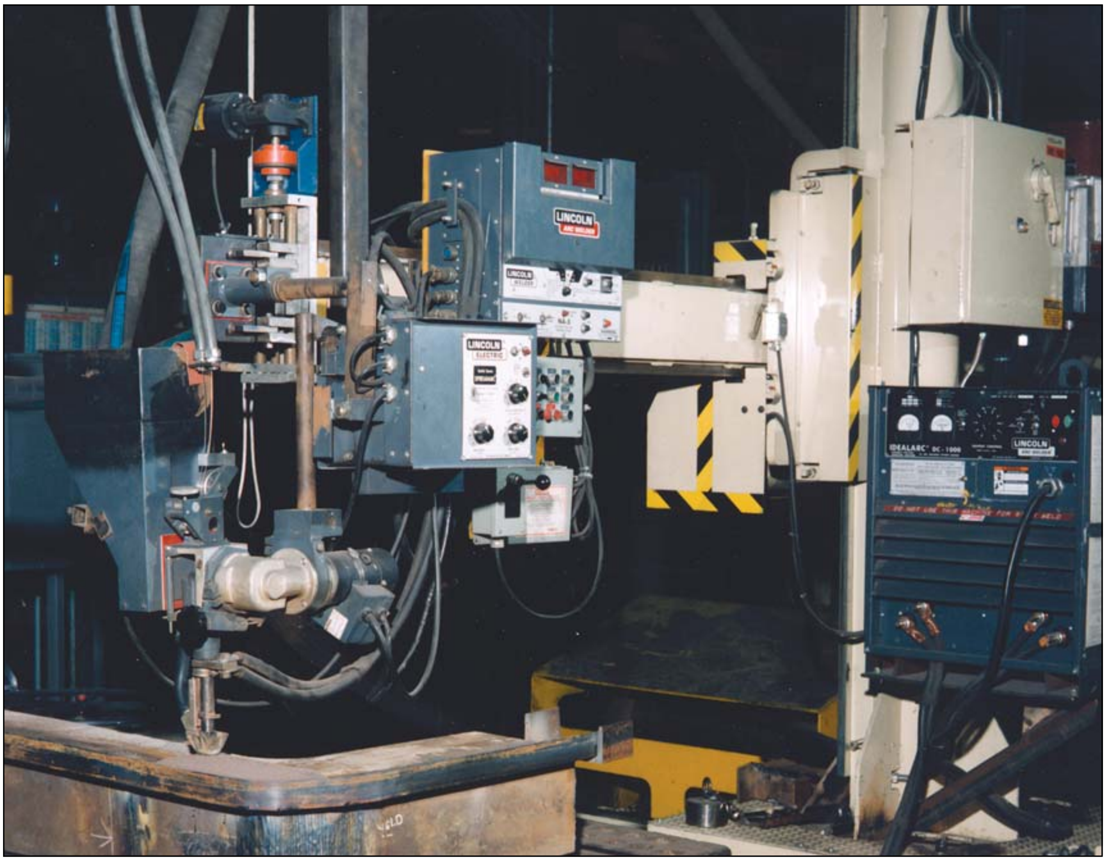
Figure 11.8—Special Mechanized System with Multiple Submerged Arc Heads

Welding fixtures are usually designed to hold one specific assembly, though minor adaptations may permit them to hold a family of similar assemblies. Automated welding also requires that the workpieces to be joined be prepared consistently and uniformly. Therefore, upstream manufacturing operations such as press stamping and forming must be able to support the close tolerances required of automated welding. The cost involved in upstream processing must be considered. Workpiece preparation costs can be reduced and fitup tolerances maintained or improved by using numerically controlled equipment in the cutting and forming areas. Workpiece preparation costs can often be partially offset by altering the design and the weld joint configuration.

Another requirement for automated welding is detailed sequential planning for each motion and operation. This includes the motions and operation of the handling equipment, the welding head, and the welding equipment (wire feeders and power sources). The operation of every device must be coordinated to begin at the correct time and location, execute the welding operation using the correct variables, and stop when the operation is complete, all while maintaining a safe environment for the operator.

Some of the advantages of a successful application of automated welding are:

1. Consistent weld quality,
2. Reduction in weld cost variability,
3. Predictable welding production rates,
4. Integration with other automated operations on the weldment,
5. Higher productivity as a result of increased welding speeds and filler metal deposition rates,
6. Increased arc-on time, and
7. Lower production costs.



Photograph courtesy of The Lincoln Electric Company

Figure 11.9—Automated Hardfacing of Earth-Moving Equipment Components

Automated welding has its limitations, however. First, automation entails a larger capital investment than that needed for manual or machine welding equipment. It also requires dedicated fixturing for accurate workpiece location and orientation. Depending on the complexity of the workpiece, elaborate arc movement and control devices with predetermined welding sequences may be needed. Finally, automation requires large-scale production to justify the cost of equipment and installation, the training of programmers, and the maintenance of equipment.

When an automated welding machine lacks the capacity to exercise complete control over the entire welding operation, the welding operator manages the process by overseeing a complex electromechanical system and promptly identifying variations from normal operation. Automated welding machines increase productivity, nevertheless, because the operator need not continually monitor the welding operations.

Under some fully automated welding conditions, the operator may do little more than load, unload, and stop the machine if it malfunctions. This normally allows the operator to perform other activities, such as the inspection of incoming parts and finished products; preventive maintenance; the supervision of other automated equipment; material handling; and housekeeping.

AUTOMATED ARC WELDING

The design of welding equipment for automated arc welding differs from that of semiautomated or manual arc welding equipment. Automated arc welding normally requires much higher duty cycles, and the welding system components must have the capacity to operate under more demanding welding conditions. As automated equipment is sometimes not readily serviceable, it must be able to run unattended for long periods.[9]

9. Design for serviceability should be considered early in the equipment specification phase.

System Components

Automated arc welding equipment can include a power source, system controller, welding interface, welding torches, a seam-tracking system, and a feeding device. These system components are described in detail below.

Power Source. A variety of power sources can be used for automated welding. The two most common types are constant voltage and pulsed arc. Automated arc welding power sources may require some special features to operate with the system controller. For example, a power source must have the capacity to communicate electronically with the controller by means of analog or digital inputs and outputs, or both. This communication is required for optimum welding performance inasmuch as multiple welding programs may be required to weld a component.

Welding schedules may change continually throughout a typical automated function. In manual welding, the welding power source controls are often adjusted by the welder to the midpoint of a welding current range that is suitable for several different welds. In automated welding, however, precise parameter adjustments can be made automatically as necessary to optimize weld quality. It is imperative that these parameter adjustments be reproduced accurately and consistently.

System Controller. All devices in the system are subordinate to the welding system controller, the primary element of an automated welding system by which each device executes its function. When so designed, each device can provide feedback on status to the controller. The controller then compares the feedback data to the planned data. If a variation is encountered, the controller calculates the required adjustment and alters the operation accordingly.

Welding Interface. The welding interface coordinates the functions of the power source and the feeder while accepting signals from the system controller.

Welding Torches. The duty cycle for automated welding equipment operates in the range of 50% to 90%. Water-cooled rather than air-cooled torches are preferred when higher duty-cycle ratings are necessary. Whereas air-cooled torches rely on no additional cooling medium (e.g., water or pressurized air), water-cooled torches require more frequent maintenance as well as the inclusion of suitable flow sensors.

Seam-Tracking System. One of the challenges in performing an automated arc welding operation is to position the welding gun or torch properly with respect to the weld joint so that the welds are produced with consistent geometry and quality. Dimensional tolerances of the components, variations in edge preparation and fitup, and other dimensional variables can affect the exact position and uniformity of the weld joints from one assembly to the next. Consequently, some adjustment of the welding gun or torch position may be required as welding proceeds along a joint.

Several systems are available to guide a welding gun or torch along a joint.[10] The simplest one consists of a mechanical seam follower system, which utilizes spring-loaded probes or some other mechanism to physically center the torch in the joint and follow vertical and horizontal workpiece contours. Of course, these systems are limited to weld joints with features of sufficient height or width to support the mechanical followers.

Other tracking systems utilize lightweight electronic probes, which operate motorized slides that adjust the torch position to follow the joint. As these devices have the ability to follow much smaller joint features and operate at higher speeds than mechanical systems, they constitute a significant improvement over mechanical seam follower systems. They are limited in their ability to trace multiple-pass and square-groove welds and are normally used with nonrobotic automation.

Still other seam-tracking systems are available with arc-sensing capability. The simplest form, an arc voltage control, is used with the gas tungsten arc welding (GTAW) and plasma arc welding (PAW) processes. This control maintains consistent torch position above the work by utilizing voltage feedback directly from the arc.

Several optical tracking systems are also available. The most sophisticated seam-tracking systems are fully adaptive to compensate for volume changes in weld joints by varying process parameters (travel speed or wire feed speed) while tracking the joint.

The single-pass or real-time system previews the operating arc and provides feedback for the correction of the torch path and welding variables. Real-time systems have difficulty with sharp corners and highly reflective surfaces. In addition, they can be influenced by smoke and arc heat. These systems also require that a camera be positioned within inches of the welding torch, which may present a clearance problem when tracking into corners and confined spaces.

In the two-pass system, a camera or laser scan is moved along the nominal weld path with the arc off. On the first pass, the system performs an analysis and weld pass correction. With the arc on, a second pass is then made to weld the joint. This system lacks the ability to correct for any distortion that occurs during welding, however.

10. For additional information on seam tracking systems, see Chapter 10 of this volume.

Feeding Device. Automated systems require a reliable, high-speed wire feeder, which is connected to the system controller and to the welding power source. The feeder allows for variable control of wire-feed rates to meet specific welding requirements. Occasional calibration of the wire feeder may be required to ensure proper performance and reliability.

Wire consumption rates are typically higher in automated arc welding than in manual welding, and the percentage of arc-on time is usually two or three times that used in semiautomated welding. Due to these high production rates, the wire conduit liners and guides frequently become clogged with debris and residual lubricants from the wire surface. Therefore, inspection and cleaning should be performed on a regular basis.

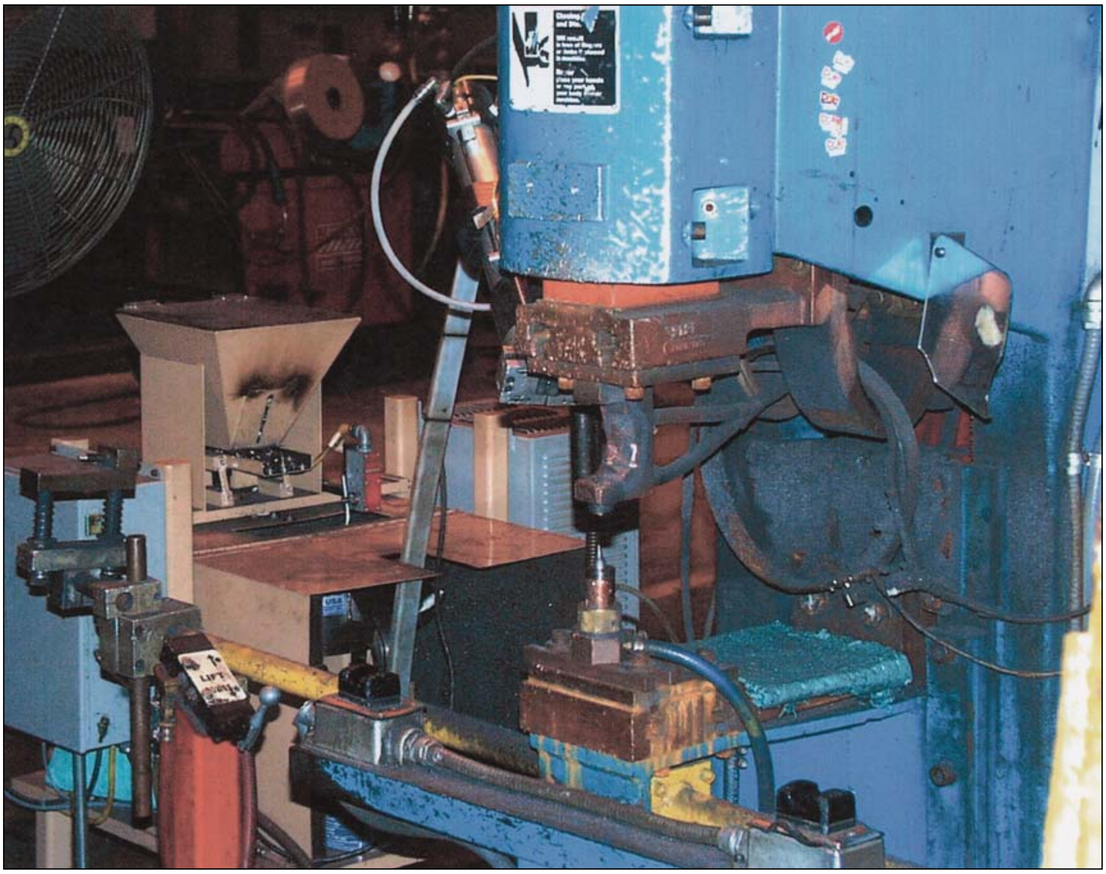
RESISTANCE WELDING AUTOMATION

The automation of resistance welding operations can range from an automated indexing fixture that positions assemblies between the electrodes of a standard resistance welding machine to special dedicated machines that perform all welding operations on a particular assembly. A typical dedicated resistance welding machine is shown in Figure 11.10. A dedicated resistance welding line is shown in Figure 11.11.

When automating a resistance spot welding application, it may be practical to move either the workpiece assembly or the welding gun to each weld location. Weight must be considered in this decision. Joining relatively thick sheets of low-resistance alloys, such as aluminum, may require large weld current conductors. Heavy welding cables may be required to carry the high currents from the power source to the welding gun.

Assemblies that weigh less than 150 pounds (lb) (68 kilograms [kg]) can be moved with most industrial robots. When an assembly is moved into position for welding, support tooling may be required to prevent damage during its movement.

In high-volume applications, such as automotive or appliance manufacturing, each welding gun in an



Photograph courtesy of Tower Automotive

Figure 11.10—Automated Resistance Welding Machine Application

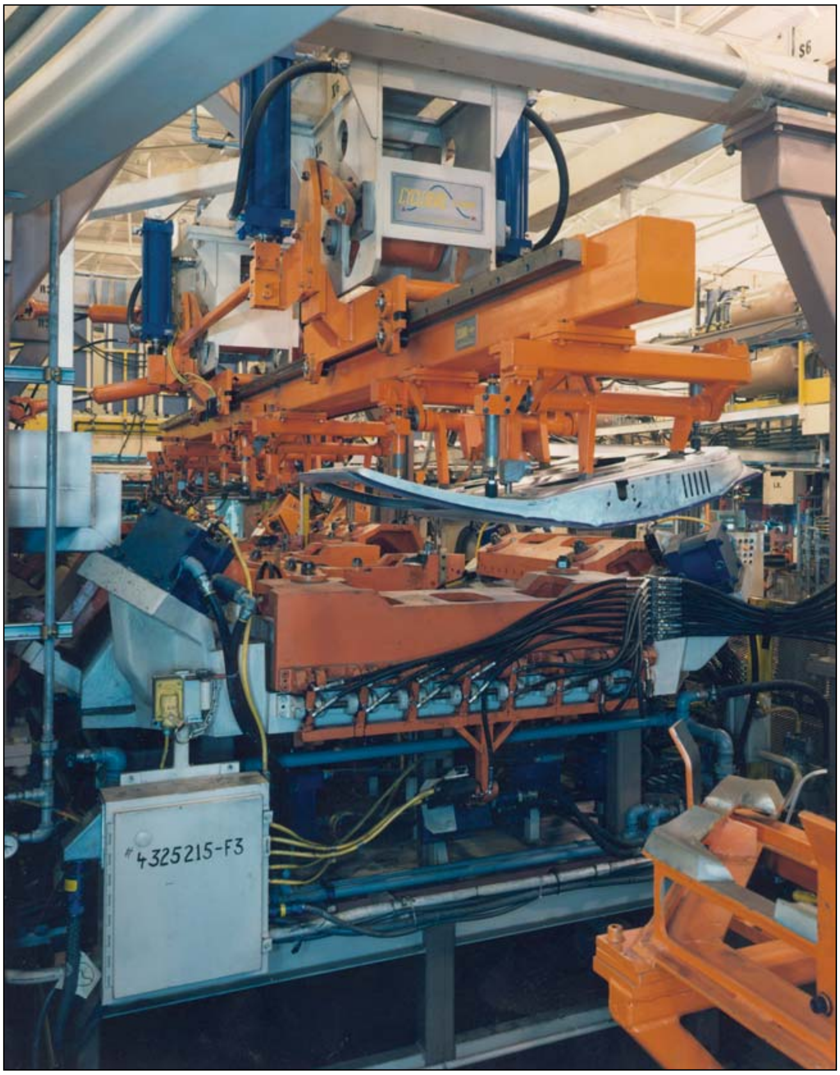


Figure 11.11—Dedicated Automated Resistance Welding Line

automated installation makes the same redundant spot welds. Production rates of 15 to 30 spot welds per minute can be achieved when the welds are in close proximity. As distances between spot welds increase, production rates depend on the maximum practical travel speed of either the welding gun or the assembly, whichever is applicable.

Production rate computations should include the following factors:

1. Transfer time between weld locations;
2. Time for the gun or assembly to stabilize in position prior to welding;
3. Welding sequence time, comprising squeeze time (typically 0 to 10 cycles), weld time (typically 5 to 20 cycles); and hold time (0 to 10 cycles);
4. Fixturing sequence time; and
5. Material handling time.

Welding cycle time can be optimized using special programming, such as welding current upslope during the latter portion of squeeze time. Likewise, welding current downslope can be applied during a portion of hold time. Hold time can be minimized by initiating the release of the gun before the weld time is completed to take advantage of the delay between the signal initiation and the retraction of the gun. A properly designed welding cycle can significantly reduce the total welding cycle time for the assembly. Care must be taken not to suboptimize by trying to weld too rapidly (the time when the welding current is on is the shortest part of the cycle), thus causing weld quality problems.

On a typical high-production application, a single welding gun makes 50 spot welds on an assembly. Increasing the welding cycle time by only 10 cycles (60 hertz [Hz]) increases the total cycle time of 50 welds by 8 seconds. Therefore, sensitive production rates can be significantly affected by very small changes in the welding cycle time.[11]

Automated Resistance Welding System Components

Automated welding imposes specific demands on resistance welding equipment. Equipment must often be specially designed and welding procedures developed to meet automated welding requirements.

Welding Electrodes. Electrode life is influenced by electrode force, the material from which the electrode is made, electrode cooling, the welding schedule, the welding current, and the type of material being welded. Upslope of welding current can greatly reduce electrode wear. Proper adjustment of the welding current upslope reduces electrode wear. Progressively increasing the current after a fixed number of welds can compensate for mushrooming of the electrodes to guarantee quality welds and allow the use of electrodes with a slightly increased contact area, thereby extending electrode life. The life of the electrode is also extended by the proper positioning of the electrodes on the joint.

Spot Welding Guns. In high-production spot welding, the time between welds must be minimized. At high welding rates, moving a light-weight welding gun may be an advantageous approach to welding relatively large, bulky assemblies. Portable spot welding guns are normally designed to accommodate the assembly. Two basic designs are the scissors and C types. Pneumatic guns are usually preferred because they are faster and apply a uniform electrode force. Hydraulic spot welding guns are normally used when space is limited or when high electrode forces are required. However, hydraulic guns may not have the consistent electrode follow-up characteristics that pneumatic guns have. Servo-controlled guns have the advantage of being easily reprogrammed for different throat openings, which can optimize cycle time.

11. Information on calculating the cost of resistance spot welding is presented in Chapter 12 of this volume.

Integral transformer gun units with up to 480 volts (V) primary can safely be used for automated welding. Power consumption is lowered with these units by closely coupling the transformer and the welding gun.

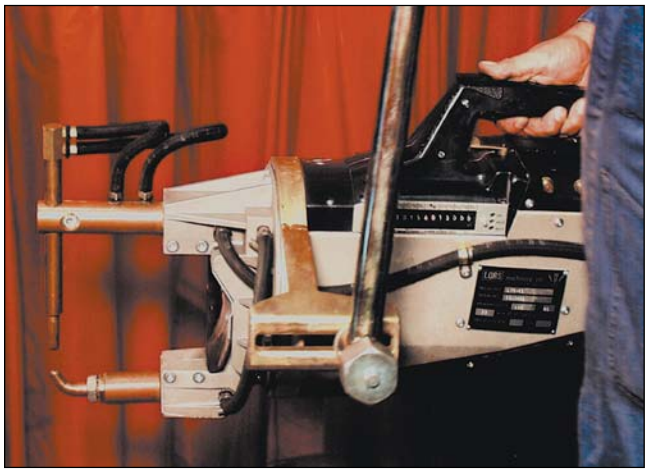
A typical resistance spot weld gun weighs 50 lb to 100 lb (23 kg to 45 kg), while the welding cable weighs another 50 lb (23 kg). A typical portable resistance spot welding gun, cable, and power source are shown in Figure 11.12.

Controls. Microcomputer controls are available to program a number of different welding schedules. An automated welding machine can be interfaced with such a control and programmed to use the appropriate welding schedule for each spot weld or group of welds.

Multiple schedule controls are commonly used in the spot welding of products such as automobile bodies and home appliances, which involve welding various gauges of sheet metal in various combinations.

Automated spot weld machines can be equipped to detect faulty or deteriorating process conditions. When teamed with optional sensory devices, such as off-flange detectors, automated spot welding machines can monitor process conditions. An off-flange detector measures the voltage between the electrodes. If the voltage or the power factor is below a set threshold value, the system signals the absence of material between the electrodes. An off-flange detector can be used to sense that a particular spot weld was not made.

Steppers, an automated function in the controller that increments the weld current a preprogrammed value every so many welds, can be used to increase the



Photograph courtesy of Tower Automotive, 2000

Figure 11.12—Portable Resistance Spot Welding Machine

welding heat automatically after a set number of spot welds to compensate for electrode mushrooming or contamination such as material pickup when welding coated material. They also signal the need to replace electrodes or indicate the need for preventive maintenance functions on the machine. The devices can also be used to measure production rates.

A current-monitoring device can indicate contaminated welding electrodes by detecting a predetermined change in welding current. Weld energy monitoring is a variation of current monitoring. The monitor is used to indicate trends or detect deterioration in equipment performance.

Resistance monitoring devices measure the change in electrical resistance between the electrodes as an indication of spot weld formation. When a resistance change occurs early in the welding cycle, the welding current can be terminated to avoid making an unacceptable spot weld. It is important to note that the output of the monitor is affected by any dirt, oil, paint, or other contaminant present on the surface of the material.

Interface Between Components. The conventional interface between an automated machine control and the spot welding equipment occurs through input-output (I/O) channels. These channels enable the machine controller to send and receive discrete signals. For example, an output signal can be sent from the machine to a welding control unit to initiate a weld. An input signal from the control unit to the machine can signal the machine to continue the operation sequence. A typical input/output communication link is described below:

1. An output signal is sent to the welding control unit to initiate the electrode force and the welding sequence,
2. An output signal is transmitted to select the programmed weld schedule,
3. An input signal is received from the welding control unit signifying that the control initiated a sequence,
4. An input signal is received from the welding control unit at the completion of the weld,
5. An input signal is received from a supervisory control to turn on an alarm or interrupt the machine operation,
6. An output signal is sent to the welding control unit to confirm that it has received the weld completion signal and is moving to the next weld location, and
7. An output signal is transmitted to a supervisory control to signal when the welding electrodes need to be redressed.

High-level communication between automated machine controls and welding controls is possible through standard communication links. These communication links permit long distance communications between central controls, welding controls, machine controls, and data acquisition centers for the following purposes:

1. In-process maintenance, such as detection of a malfunctioning silicon controlled rectifier (SCR) or a missed weld;
2. Continuous in-process monitoring of welding current, power, or electrical resistance for quality control;
3. Monitoring of equipment's status and condition;
4. Coordination of equipment activities;
5. Monitoring or reporting of production output; and
6. In-process modification of programs or schedules.

Ancillary Equipment. In addition to the basic system components, ancillary devices such as monitors and adaptive process control may be required to ensure consistent quality.[12] Weld monitors provide nondestructive quality assurance information. If weld quality data are difficult to obtain through random or periodic destructive testing, weld monitors may be an alternative. Data can be recorded for review later.

Monitors can reduce the amount of destructive testing required. Only welds of questionable quality need to be examined. Monitoring data and periodic destructive testing can provide an effective quality control program.

Monitoring equipment can perform some or all of the following functions:

1. Sense position to detect the presence of a component (e.g., a projection nut);
2. Measure the weld current or power to detect long-term changes to indicate the need for cable and gun maintenance;
3. Measure the welding voltage to detect the absence or presence of a workpiece;
4. Measure resistance or impedance to detect the formation of a weld;
5. Sense electrode position to detect the movement of electrodes, signifying weld formation;
6. Measure ultrasonic reflection from a weld to verify the weld size for quality control; and
7. Perform acoustic emission detection and analysis of sound emitted from a weld as it forms to determine weld size or the presence of discontinuities.

12. For additional information on ancillary equipment see Chapter 10.

A welding process is considered adaptively controlled when changes in weld integrity are measured and corrected in real time. The sensors listed above can be used to detect certain properties of spot welds. These inputs can be analyzed and acted upon by an adaptive control program to optimize or correct the welding schedule variables. Users of adaptive controls are cautioned to test and evaluate the controls thoroughly before abandoning established quality control programs.

Quality Control

A benefit of resistance welding automation is improvement in quality control. However, weld quality is dependent upon process control inasmuch as an automated spot welding machine indiscriminately repeats objectionable welds as well as acceptable welds.

An automated spot welding machine can maintain acceptable spot weld quality with feedback controls and appropriate electrode maintenance. For example, an automated head is normally programmed to position the plane of the welding gun perpendicular to the weld joint. In contrast, in manual spot welding, an operator can easily misalign the welding gun as a result of fatigue, boredom, or carelessness. This condition may result in improper welding pressure and weld metal expulsion from the seam, potentially reducing the quality of the joint.

When different thicknesses of metal are to be spot welded using the same welding gun, an automated spot welding machine can be programmed to use a different welding schedule for each thickness. Weld quality is improved when the proper welding schedule is used for each joint thickness.

ROBOTIC WELDING

The term *robot* is defined by the Robotic Industries Association (RIA) as "an automatically controlled, reprogrammable multipurpose manipulator programmable in three axes or more which may be either fixed in place or mobile for use in industrial automation applications."[13] Industrial welding robots incorporate many forms of multiaxis, servo-controlled manipulators that are equipped with software to allow them to perform complex, continuous welding processes. The welding program can be changed to handle new workpieces, a variation in existing workpieces, or a change to the weld seams only.

Industrial robots were initially introduced for commercial sale in the United States in 1961. Though these product offerings were not suited to arc welding applications, they were adapted for resistance welding in the automotive industry by 1964. The first multiaxis robot suitable for arc welding applications was introduced in 1972, though the use of welding robots did not proliferate until the late 1970s. In the 1980s, resistance welding robots drove the market with respect to sales. In the 1990s, robotic arc welding equipment grew as a percentage of new robot sales, especially outside the automotive industry.

Robots are ideally suited to both arc and resistance welding for various reasons. Robots are capable of working in hostile environments as they are immune to the difficulties presented by radiation, fumes, heat, and other hazards. They offer repeatability and reliability and adapt to the physics of the welding process based on sensory input. In addition, robotic welding systems have the flexibility to change from one welding routine to another in an almost uninterrupted fashion.

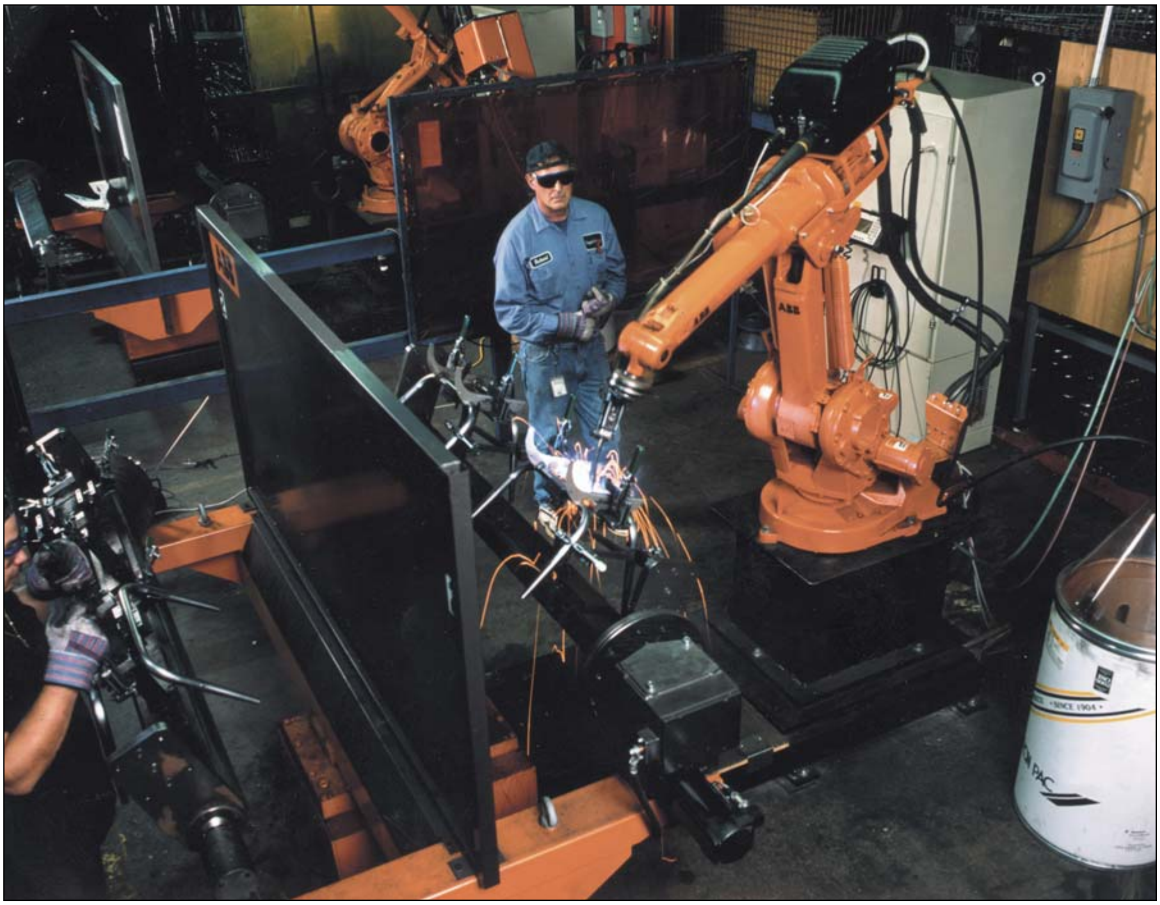
Historically, flexible automated welding or robotic systems have been more expensive than other automated or mechanized equipment. However, robots have decreased in cost while their capabilities and ease of operation have steadily improved. On the other hand, the costs of fixed automation have remained consistent while the overall capabilities have only slightly improved. To select the optimal system for a given job, a comparative study should be undertaken to determine the true life-cycle cost for each system under consideration.

Despite their added expense, welding robots seize a larger portion of the welding market every year from manual, mechanized, and other fixed and flexible automation methods. Though cost is an important factor in the selection of a process application method, the decision to incorporate welding robots is typically driven by several factors. These include flexibility, longevity, product quality, ergonomics, and worker health and safety.

ROBOTIC ARC WELDING SYSTEMS

Most robotic arc welding systems utilize the gas metal arc or flux cored arc welding processes. Arc welding robots are prevalent in the automotive and construction industries, but general industry, predominated by smaller manufacturers, is the fastest growing segment. A typical robotic arc welding system is pictured in Figure 11.13.

13. Robotic Industries Association (RIA), 1999, *American National Standard for Industrial Robots and Robot Systems—Safety Requirements*, ANSI/RIA R15.06-1999, Ann Arbor, Michigan: Robotic Industries Association, p. 4.



Photograph courtesy of Tower Automotive, 2000

Figure 11.13—Robotic Arc Welding

System Components

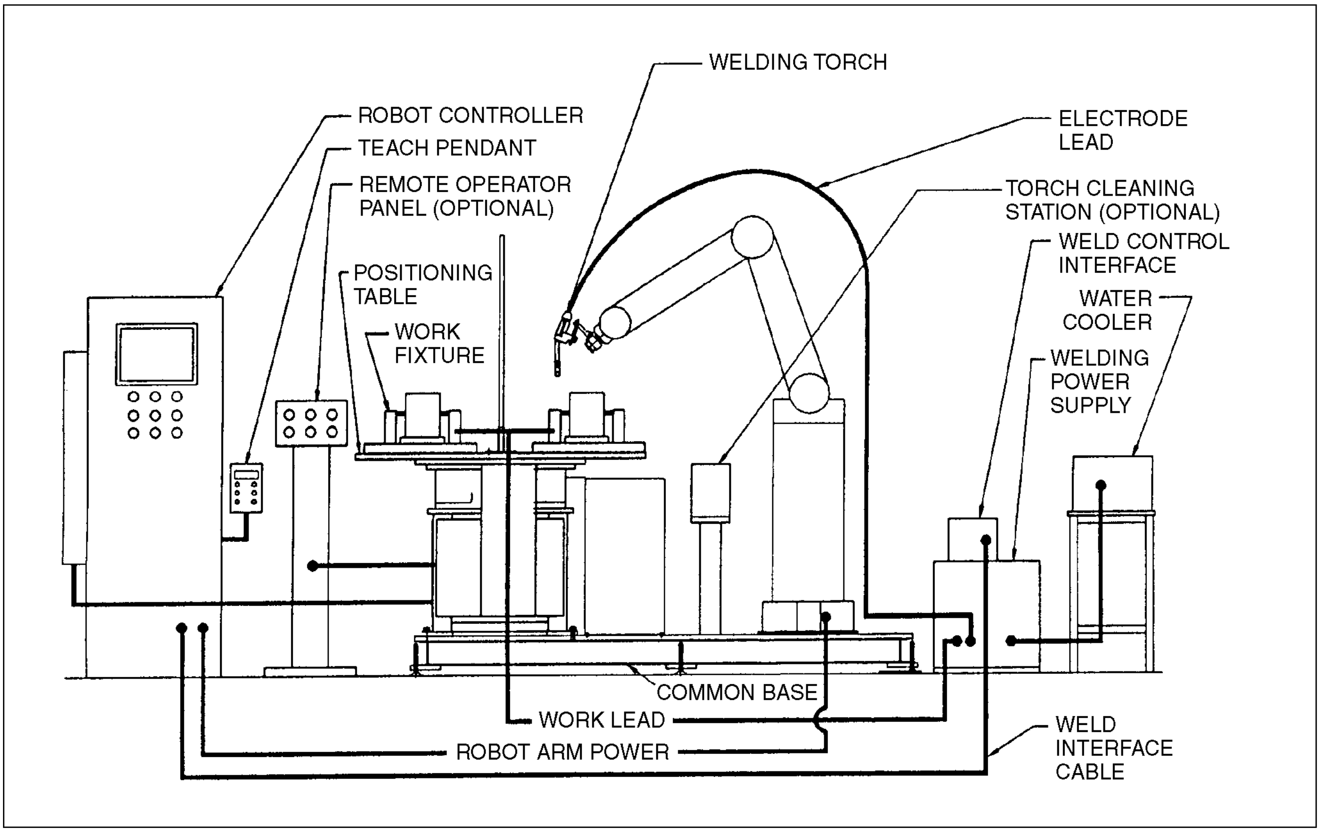
A typical robotic arc welding system such as that depicted in Figure 11.14 is composed of the following ten primary components:[14]

1. Manipulator,
2. Arc welding power source,
3. Arc welding torches and accessories,
4. Dereeling system,
5. Welding interface,
6. Shielding gas delivery system,
7. Welding electrode feeding equipment,
8. Welding circuit,
9. Communication control wiring, and
10. System grounding.

Peripheral Equipment. Robotic arc welding systems include a variety of peripheral equipment. The type and amount of peripheral equipment depends on the application and the budget available. Recommended optional equipment includes a water cooler/chiller, torch cleaner, and tool center point (TCP) locator. Additional axes of motion are sometimes required and would involve a positioner, robot track, or movable gantry. Computer intelligence in the form of seam finders and seam trackers is sometimes required to handle workpiece movement and poor fitup.

Robotic welding systems typically have controls and associated fixturing and safety systems. The robot system usually possesses a programmable logic controller (PLC), which ensures that all operations occur safely in

14. For further information, see American Welding Society (AWS) Committee on Robotic and Automatic Welding, *Standard for Components of Robotic and Automatic Welding Installations,* ANSI/AWS D16.2, Miami: American Welding Society.



Source: American Welding Society (AWS) Committee on Robotic and Automatic Welding, 1994, *Standard for Components of Robotic and Automatic Welding Installations*, ANSI/AWS D16.2-94, Miami: American Welding Society, Figure 1.

Figure 11.14—Schematic of a Typical Robotic Arc Welding System

the correct sequence. The fixturing can consist of manual, pneumatic, or electromechanical clamping. The safety system employed depends entirely on the type of application. Torch safety mounts, light curtains, safety mats, and enclosures are some of the features designed to ensure a safe system. Safe practices require that the final installation of equipment conform to current published safety regulations.

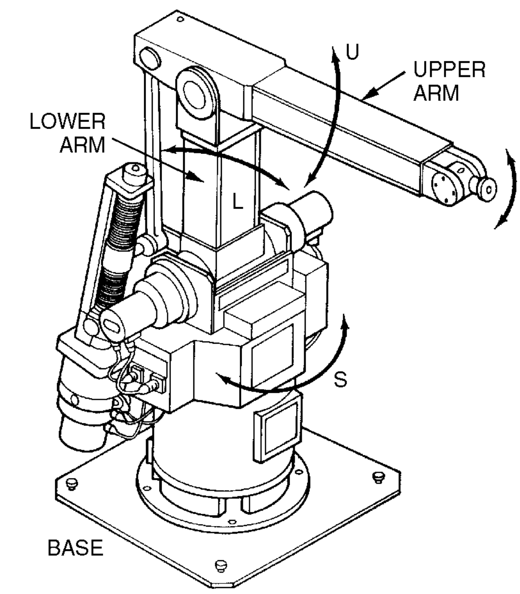
Operating Characteristics

Robotic arc welding systems are categorized according to (1) motion capabilities and working reach, (2) load capabilities, and (3) maximum working velocity. These systems are characterized by repeatability, accuracy, high productivity, and reliability.

Motion Capabilities. The two most common types of robots are articulated and rectilinear. Articulated robots, which typically have six axes, can be used for arc welding when outfitted with the correct process-specific hardware and software. Because of their versatility and cost-to-performance ratio, articulated robots represent more than 90% of the robots sold for arc welding. Rectilinear robots, which typically have fewer than six axes and limited torch-orientation capacity, are used more in specific niche applications, such as in large gantry systems for shipyards. Figure 11.15 presents an illustration of an articulated robot, while Figure 11.16 features a rectilinear robot.

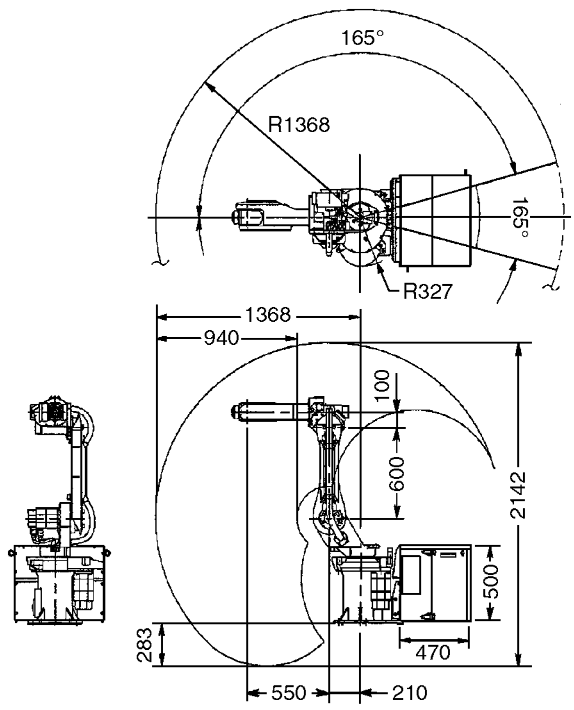
The primary type of robot used for arc welding is the six-axis articulated arm robot. The six degrees of freedom function in a manner similar to the human arm. This robot offers maximum flexibility for weld torch positioning and orientation. The work envelope for a typical arc welding robot is illustrated in Figure 11.17. When planning a work cell, the workpiece must be located comfortably within the envelope.

Load Capacity. Arc welding robots typically have an end-of-arm load capacity of 6.6 lb to 35.2 lb (3 kg to 16 kg). Robots also have a payload capability at other



Source: Adapted with permission from Cary, H. B., 1994, *Modern Welding Technology*, 3rd ed., Englewood Cliffs, New Jersey: Regents/Prentice Hall, Figure 12-43.

Figure 11.15—Schematic Illustration of an Articulated Robot



Courtesy of Fanuc Robotics North America, Incorporated

Figure 11.17—Work Envelope for a Typical Arc Welding Robot

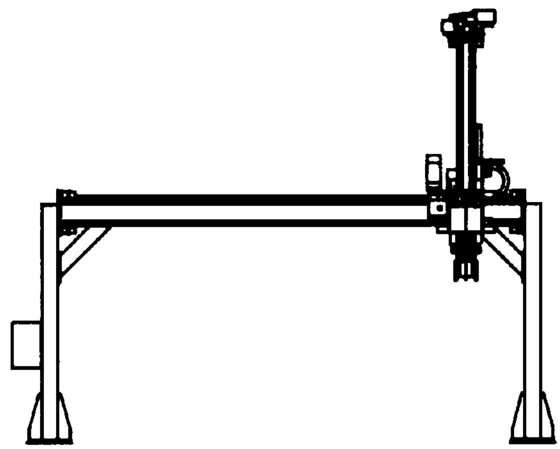
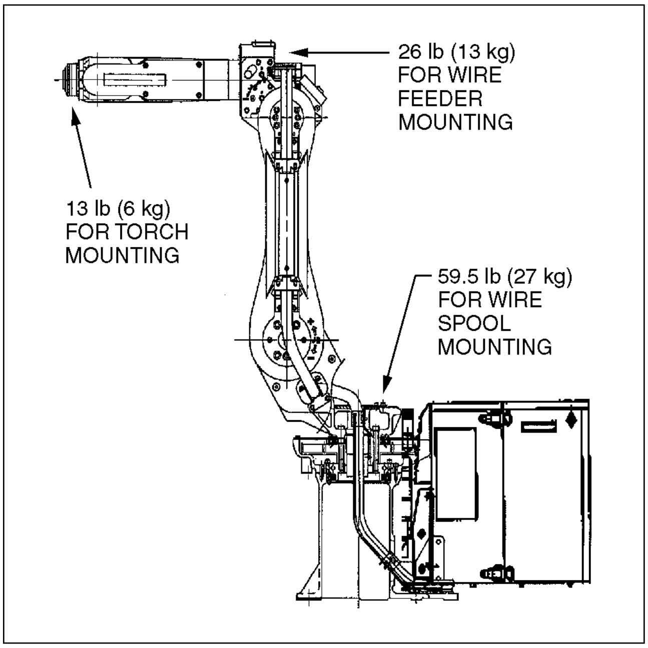


Figure 11.16—Schematic of a Rectilinear Gantry Robot

arm locations that allow mounting of peripheral equipment such as wire feeders and wire spools. A typical arc welding robot payload distribution is shown in Figure 11.18.

Repeatability and Accuracy. Repeatability is defined as the ability of a robot to return precisely to a programmed position. Robots have the capacity to be extremely repeatable. The typical repeatability of arc welding robots is rated better than ± 0.004 inch (in.) (± 0.1 millimeter [mm]). In other words, the welding torch returns to within 0.004 in. (0.1 mm) of the same point after each program is executed.

One of the most dramatic improvements in robot performance in recent years has been with respect to accuracy. Accuracy is defined as the ability of a robot to move a predetermined distance and direction, and the ability to follow a path precisely between programmed points. This is difficult to quantify, and it typically varies depending on the location in the robot's work envelope.



Courtesy of Fanuc Robotics North America, Incorporated

Figure 11.18—Typical Robot Payload Distribution

The increased use of off-line programming has increased the importance of accuracy. In off-line programming, the points are not oriented to the actual workpiece. Instead, they are entered as numeric locations in the robot's workspace. With greater robot accuracy, less adjustment before production is required of programs generated off-line.

Productivity. Under the correct conditions, robots offer a tremendous return on investment. The break-even point usually occurs between the first and the third year, depending on labor wages, production volume per year, and the cost of the robotic cells. In the late 1990s, the cost of a conventional cell for an assembly-line arc welding station ranged between $60,000 and $100,000.

Productivity gains are achieved because robots produce quality welds with great consistency at high travel speeds. Manual welding typically operates at the rate of 20 in./min to 45 in./min (0.08 mm/sec to 1.9 mm/sec), whereas robotic welding operates at 40 in./min to 100 in./min (1.7 mm/sec to 4.2 mm/sec), process permitting.

Greater consistency permits the weld size to be held closer to specification. For example, when an operator manually creates a 0.12 in. (3 mm) fillet weld 2.4 in. (60 mm) long in a workpiece, the weld typically becomes a 0.10 in. to 0.25 in. (4 mm to 5 mm) fillet that is 2.5 in. to 2.75 in. (65 mm to 70 mm) long. However, when this same operation is performed by a welding robot, a 0.12 in. to 0.14 in. (3 mm to 3.5 mm) weld can be produced consistently over the entire 2.4 in. (60 mm). Consequently, robots dramatically reduce the occurrence of oversized welds, thus saving consumables.

Reliability. Industrial robots are highly reliable. They are typically designed to last from 8 to 10 years, with a minimum mean time between failure (MTBF) of 20,000 hours. Robots themselves are relatively maintenance free, requiring only periodic lubrication. Most robotic components that are susceptible to failure are designed to permit quick replacement in the production environment. The welding equipment incorporated into a robotic weld system is also very reliable, given proper preventive maintenance.

Programming

Robotic arc welding systems must be programmed in order to perform a welding operation. Programming is the creation of a detailed sequence of steps that the robot must follow to weld the assembly successfully according to specifications. Each assembly to be welded requires an investment in programming. Programming costs vary widely depending upon the robotic welding system being used, the experience of the programmers, the complexity of the welding process, and the programming method. Investment in programming must be taken into account when evaluating the economics of automated welding. Once a program is written for a specific weldment, the program can be stored for future use.

Program development involves the following steps:

1. Calibrating the automated or robotic welding system to ensure that the robot will operate from a known set point every time a particular program begins. Some robot manufacturers have tools that automatically calibrate the robot's tool center point, including the torch angle;
2. Establishing the location of the assembly with respect to the welding machine and verifying the weld process for the weld joints to establish weld positions and limitations. Adjustments may need to be made to the tool center point for the best accessibility and angle management;
3. Determining the path to be followed by the welding torch as welding progresses. Some robots are "taught" the path, while other robotic welding systems may be programmed off-line;
4. Developing the welding conditions to be used. Welding conditions must be coordinated with the robot's work-motion program; and

5. Refining the program by checking and verifying performance. Programs often require editing to correct the torch path and obtain the desired weld profile.

The process of "teaching" a robot can be time consuming, especially when productive robot time is lost. Off-line programming using computer-aided manufacturing (CAM) systems can be used to program the sequence of motions of the robot and positioner. The robot can remain in production while the programs are developed off-line. This makes smaller batch sizes more feasible in robotic applications. Graphic animation programs help visualize, debug, and edit the motion sequence program off-line.

Programs for automated welding are usually evaluated using actual production workpieces or parts. Simulated production parts cannot duplicate the effects of distortion, heat input, and clamping. Simulated parts should be used only in the initial stage of process development. To produce prototypical parts, the best approach is to weld them using procedures and equipment that are as similar as possible to those used in production. If problems arise early in the program, they can be addressed before the project is launched into production. An inexperienced user should consult with the equipment manufacturer or other experts to determine suitable equipment and associated parameters for developing prototype parts.

Common Software Options

Robot controllers are equipped with standard welding software. This software provides the necessary logic to program and execute most welding functions. Optional software programs can be obtained from most robot manufacturers for use with unique operations. Common arc welding software options permit tool center point correction, touch sensing, and through-the-arc seam tracking.

Tool center point correction software performs a check of the wire placement in relation to the programmed tool center point. If the software detects that the welding wire has been moved off location due to a worn contact tip or a bent torch, the robot automatically adjusts the tool center point to the present welding wire location.

Touch sensing software allows the robot to locate the workpiece by touching it with either the welding torch or the wire extended from the contact tip to determine whether the workpiece is in the correct location. The program shifts as necessary to accommodate to the new location or orientation of the workpiece.

Through-the-arc seam-tracking software is designed to allow the robot to perform real-time seam tracking by oscillating the torch while in the joint and monitoring variations in welding current to keep the weld in the joint. Newer software is capable of tracking thin-gauge (i.e., greater than 3/16 in. [5 mm]) lap welds at welding speeds up to 50 inches per minute.

Most welding software programs provide a means to download existing programs for off-site storage and retrieval.

Maintenance

Preventive maintenance activities for robotic arc welding equipment are conducted in sequence along the path of the weld wire. Thus, attention must be paid to the dereeler, conduit, feeder, and torch. The front-end consumables—tip, nozzles, and diffuser—need frequent replacement. Peripherals such as the torch cleaners and torch mounts also require periodic inspection.

Qualification of Robotic Arc Welding Personnel

Robotic arc welding equipment is becoming more inexpensive, while its inherent reliability is higher. However, many companies do not attain the productivity required from their robotic arc welding systems due to a lack of qualified personnel. For further information on this topic, the reader is encouraged to consult *Specification for Qualification of Robotic Arc Welding Personnel,* AWS D16.4.[15]

Risk Assessment Guidelines

Robotic arc welding systems have historically been very safe. However, the wide variety of potential hazards associated with robotic operations require great care in planning a system. For further information about risk assessment, the reader can consult the American National Standard *Risk Assessment Guide for Robotic Arc Welding*, AWS D16.3,[16] and the *American National Standard for Industrial Robots and Robot Safety Systems—Safety Requirements,* ANSI/RIA R15.06.[17]

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15. American Welding Society (AWS) Committee on Robotic and Automatic Welding, *Specification for Qualification of Robotic Arc Welding Personnel*, AWS D16.4, Miami: American Welding Society.
16. American Welding Society (AWS) Committee on Robotic and Automatic Welding, *Risk Assessment Guide for Robotic Arc Welding*, AWS D16.3, Miami: American Welding Society.
17. Robotic Industries Association (RIA), *American National Standard for Industrial Robots and Robot Systems—Safety Requirements*, ANSI/RIA R15.06, Ann Arbor, Michigan: Robotic Industries Association.

ROBOTIC RESISTANCE WELDING SYSTEMS

When flexibility is required in an automated resistance welding operation to handle various assemblies, a robotic installation is a judicious solution. An example is the robotic spot welding line for automobile bodies shown in Figure 11.19. An installation of this type can be programmed to spot weld various locations on the same car body and similar car bodies of various models.

Types of Resistance Welding Robots

Industrial resistance welding robots can be grouped into four general geometric classifications. Rectilinear or Cartesian coordinate robots have linear axes, usually three in number, which move a wrist in space. Their work envelope is box-shaped. Cylindrical coordinate robots have one circular axis and two linear axes. Their work zone is cylindrical. Spherical coordinate robots employ two circular axes and one linear axis to move the robot wrist. Their work zone is spherical. Articulating (jointed arm) robots utilize rotary joints and motions similar to those of the human arm to move the robot's wrist. Their work envelope has an irregular shape.

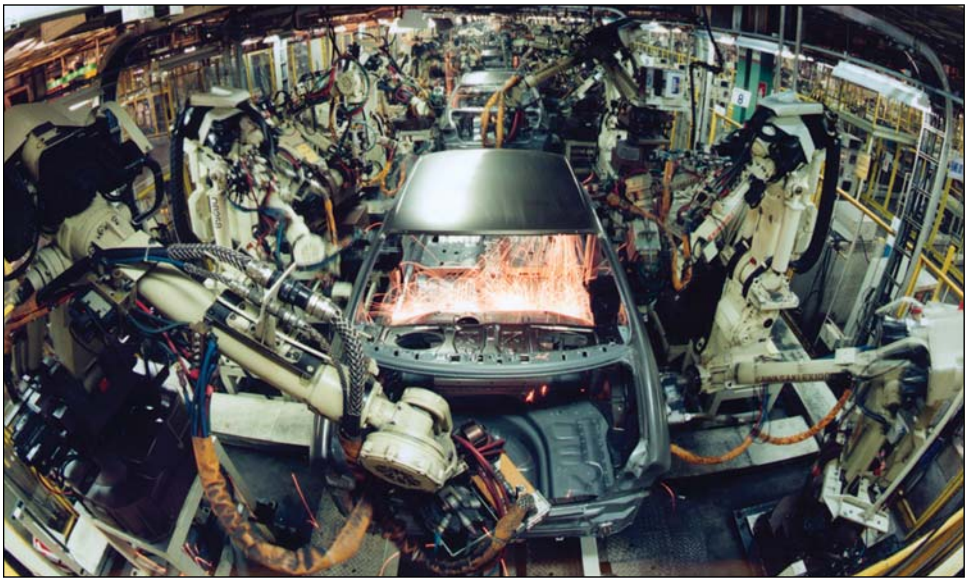
All four robot geometries perform the same basic function—the movement of the robot's wrist to a location in space. Each geometry has advantages and limitations under certain conditions. For example, articulating and rectilinear robots are favored designs for arc welding.

Operating Characteristics

The selection of the appropriate robot for a given application depends on a number of essential characteristics. These include working reach, load capacity, accuracy and repeatability, and reliability.

Working Reach. Spot welding robots should have six or more axes of motion and be capable of approaching points in the work envelope from any angle. This permits the robot to be flexible in positioning a welding gun to weld an assembly. In the case of an automobile, a door, a window, and a roof can all be spot welded at one workstation. Some movements that are awkward for an operator, such as positioning the welding gun upside down, are easily performed by a robot.

Load Capacity. Most spot welding robots are designed to manipulate welding guns weighing from 75 lb to 150 lb (34 kg to 68 kg). Manual spot welding guns are often counterbalanced using an overhead support that can limit positioning of the gun. Robots with sufficient load capacity can move spot welding guns without counterbalances. Counterbalances may be needed to support heavy welding cables unless low-



Photograph courtesy of Fanuc Robotics, Incorporated, 1999

Figure 11.19—Dedicated Automated Resistance Welding Line

weight integral spot welding gun-transformer units are used.

Careful consideration must be given to robotic resistance welding applications because the current conductors may exceed the load-carrying capacity of the robot. One solution is to move the assembly into position and weld with a stationary or indexing spot welding machine. Alternatively, the assembly may be indexed while single spot welds are made with a stationary welding machine.

Accuracy and Repeatability. The accuracy and repeatability offered by resistance welding robots vary from model to model. A robot can repeatedly move the welding gun to each weld location and position it perpendicular to the weld seam. It can also replay programmed welding schedules. A manual welding operator is less likely to perform as well because of the weight of the gun and monotony of the task. However, whereas an operator can detect and repair poor spot welds, spot welding robots cannot.

Both high- and low-volume applications can be welded with robotic resistance welding equipment. In low-volume applications such as aerospace work, a welding robot can be used to fabricate a number of various spot welds before repeating an operation. Some robot models require periodic recalibration or reprogramming to ensure accurate functioning.

Reliability. Industrial robots with duty cycles of 98% or better are currently capable of 20,000 hours of operation between failures. Robots are capable of operating continuously, as long as proper maintenance procedures are followed. On continuous lines with multiple robots, interruption of production can be minimized by (1) installing backup units in the line, (2) distributing the work of an inoperative robot to other nearby robots, or (3) quick replacement of the inoperable robot.

Assembly Program Development

The first step in the development of a program for an assembly is to establish a welding schedule for each proposed material and thickness combination. A robot can be "taught" the sequence of welding positions with the plane of the welding gun perpendicular to the seam. The sequence of weld positioning should be chosen to minimize the repositioning and index time for the robot. Finally, a travel speed between weld locations is selected. It should not be so high that oscillation or overshooting of the electrodes takes place. Appropriate welding schedules are selected and programmed at each welding position.

The editing changes that are made in welding programs to improve or correct automated operations are referred to as *touch-up programs*. Typical reasons for editing include the following:

1. Dimensional changes in the workpieces;
2. Optimization of welding variables to improve weld quality;
3. Optimization of gun movements and speeds to increase production rate;
4. Changes in fixturing location; and
5. Correction for movement, drift, or calibration changes.

Maintenance

In addition to the recommended maintenance of the robot, maintenance of the resistance welding equipment is necessary. On a monthly or weekly basis, the electrical shunts should be tightened or replaced, as needed. Worn or damaged welding cables should be replaced. Leaking air or hydraulic pressure lines should be repaired or replaced, as required, as should leaking or damaged air or hydraulic system regulators. In addition, welding transformers that show signs of deterioration should be replaced.

Daily maintenance includes inspecting electrical cables for shorts, tightening loose bolts, inspecting for oil or water leaks, cleaning the robot's surroundings, and reporting maintenance findings to the supervisor. On an hourly basis or after a specific number of welds, the resistance welding electrodes should be reground, repaired, or replaced, as needed.

PLANNING FOR AUTOMATED AND ROBOTIC WELDING

Automation involves more than equipment and computer controls. It is a way of organizing, planning, and managing a production process. The procedures, systems, and production controls used for manual welding cannot always be adapted to automated welding inasmuch as most manual welding methods rely heavily upon a welder's knowledge, skill, and judgment.

When considering conversion to an automated or robotic system, a thorough evaluation of the intended application method should be made to ensure its success. An analysis of all manufacturing and monetary variables, including those discussed below, should be performed before acquiring capital equipment for an automated or robotic welding cell.

PRODUCTION VOLUME

Production volume must be considered when deciding whether to automate an operation. Fixed automation may be appropriate when production levels are expected to remain high for a limited number of parts. Weld seam geometry should be simple and repeatable for the automated cell to be productive. Generally, fixed automation employs a maximum of three axes of motion for the welding process.

Flexible automation is well suited for small or large production volumes. It can be designed to accommodate complex weld seam geometries and programmed to weld different, unrelated parts, allowing for high utilization of the cell and smaller lot sizes. Flexible welding systems can control and change welding variables more effectively than fixed automation, yielding less arc time required per weldment and more arc time per hour. Process optimization results in lower cycle times and higher utilization of production time.

PRODUCT DESIGN

Special design considerations are required for automated and robotic welding. Joint designs and joint placements that optimize the repeatability of joint location and fitup should be considered. Because component strength requirements may differ as compared to those required for manual welding, appropriate tests should be conducted to determine the mechanical properties of the joints to be fabricated using the proposed automated joining equipment. Design changes that recognize the increased consistency and reliability of automated welding also contribute to the reduction of material and consumable costs.

When adapting an arc welding operation to automation, the following factors must be considered with respect to product, tooling, and fixture design:

1. Access to the joint by the welding torch or robot;
2. Addition of location features on the workpiece;
3. Use of subassemblies to simplify the weldment, as needed;
4. Avoidance of out-of-position welds;
5. Redesign of weld joints that are difficult to control;
6. Use of lap or fillet welds, which are easier to produce than edge or corner welds;
7. Use of a common dimensional reference to locate and relocate parts;
8. Consideration of the sequence for the loading of parts and unloading of finished weldments;
9. Positioning of the parts in a repeatable manner;
10. Design of clamps and fixtures to account for potential distortion caused by the welding process;
11. Clamping as close to the weld joint as practical;
12. Use of locators on surfaces that can be controlled and avoidance of bent or formed surfaces and long stretches that may be subject to springback after forming;
13. Appropriate stacking of part tolerances to avoid movement of the weld joint outside of the permissible weld process tolerance;
14. Use of automated clamping where appropriate; and
15. Limiting the use of tack welds and attempting to make them small and repeatable, when used.

Additional costs incurred in the correction of deficiencies must be considered when estimating automation's return on investment.

Workpiece tolerances and joint fitup are extremely important in achieving consistently high quality in automated and robotic arc welding. Accepted general industry tolerances for the relationship between the energy source and the joint are as follows:

1. For gas metal arc welding, ± 1/2 electrode diameter;
2. For gas tungsten arc welding, ± 1/2 electrode (tungsten) diameter; and
3. For laser beam welding, ± 1/2 focused beam diameter.

The accepted general industry tolerances for gaps are as follows:

1. For gas metal arc welding, the material thickness or 0.060 in. (1.5 mm), whichever is less, and
2. For laser beam welding, 10% of thinnest material thickness.

The tolerances presented above are for the gas metal arc and gas tungsten arc welding of steel. Aluminum requires location and root opening tolerances that are half as large. If the joint-to-electrode geometry is consistent, robotic welding can be performed without adaptive feedback controls.

The manufacturing processes used in the preparation of component parts must be reviewed for consistency. In addition, the cost of improving component consistency must be included in the financial analysis.

PROCEDURES AND SCHEDULING

The procedures and scheduling systems used in most shops were initially developed for manual welding. Conversion to automation requires the development of new procedures and scheduling methods to maximize productivity. This warrants a detailed review of subassembly design and component scheduling. Often, an entire family of assemblies can be fabricated with one flexible automated welding system.

Conversion to automated or robotic welding may require a modification in welding procedures and quality control methodology. For example, periodic destructive or nondestructive examination and inspection may be required for quality control. Additional quality control tests, such as joint fit-up inspection, may also be required. Multiple welding operations may be combined at a single workstation. Welding process parameters, machine control programs, and other information may need to accompany components or planning sheets. New process specifications and acceptance criteria may be required. In addition, compliance with state, local, and federal safety regulations should be re-evaluated, and networking and integration with other manufacturing processes must be considered.

FIXTURING

When assemblies are redesigned or procedures are changed in the conversion to automation, new welding fixtures are often required. Fixturing for automation is likely to cost more per fixture; nevertheless, an automated operation may be more efficient because it requires fewer fixtures. Robotic fixtures must locate the weld joint more accurately unless seam-tracking systems are incorporated. To locate joints accurately, additional positioning aids such as workpiece tabs, clamp position sensors, and workpiece presence sensors are built into the workpieces and welding fixtures.

PROCESS SELECTION AND WELDING PROCEDURE QUALIFICATION

Converting to automated or robotic welding may entail a change in the welding process. The product design and upstream manufacturing processes might also require modification. It is imperative to select the appropriate welding process and associated welding consumables for the specific operation.

Procedures for automated and robotic welding should be qualified according to applicable welding standards, such as *Structural Welding Code—Steel*, AWS D1.1.[18] In the absence of a specific standard, *Standard for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1,[19] should be used.

WELD DEVELOPMENT AND TESTING PROGRAM

When conversion to automation is being considered, a weld development and testing program should be implemented to ensure that optimum welding performance is obtained from the proposed investment in capital equipment. The objectives of this program include (1) optimizing weld quality and consistency; (2) evaluating the effects of distortion, fit-up tolerances, heat buildup, weld spatter, surface conditions, and other factors; and (3) ensuring the availability of representative welded specimens for testing and evaluation.

MANUFACTURING FEASIBILITY STUDIES

Studies are conducted to guarantee the feasibility of the manufacturing process. These studies may incorporate current production components, prototypes, or computer simulations. All pertinent factors—workpiece weight, moments of inertia, fixturing configuration, and so forth—should be examined. Common objectives of manufacturing feasibility studies include the following:

1. Suitability of the product design for automated operations,
2. Establishment of working relationships with equipment manufacturers,
3. Determination of production sequences and cycle times (including setup, indexing, welding, and unloading times),
4. Evaluation of critical operator skill and safety requirements, and
5. Proof of accessibility to the welds using computer simulation or physical mockups.

SELECTION OF WELDING EQUIPMENT

Automated and robotic welding systems must operate at high duty cycles to justify the investment. These high duty cycles necessitate the use of rugged, heavy-duty welding equipment designed for continuous operation. Water cooling should be specified, as applicable, to avoid overheating of the welding equipment.

User requirements are generally written for custom-designed machines. These specifications are detailed on the purchase or lease order. Equipment and process

18. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society.

19. American Welding Society (AWS) Committee on Welding Qualification, *Specification for Welding Procedure Qualification,* ANSI/AWS B2.1, Miami: American Welding Society.

specifications define the performance expectations of the purchaser and the supplier and establish minimum quantitative requirements for defining the equipment. They provide uniform criteria to allow the evaluation of several vendors' proposals and facilitate the formation of support groups with a background in maintenance, programming, and other disciplines to prepare for delivery of the equipment. Specifications also allow customers to negotiate details with the supplier to secure the best equipment performance for the best price.

INTEGRATION OF THE AUTOMATED OR ROBOTIC SYSTEM

Manufacturers use several approaches when implementing robotic arc welding systems. Whereas some prefer a turnkey weld system supplied from an integrator, others prefer to integrate discrete components. Regardless of the approach, responsibilities should be established with respect to operating, preparing, and testing the automated equipment before it is purchased.

Specific areas of responsibility include the site preparation and preliminary engineering required to support equipment installation; the scheduling of delivery, training, installation, and startup; and achieving performance criteria (throughput/cycle time, up time, dimensional tolerances, weld quality, and so forth).

Various responsibilities should not be overlooked when integrating automation into production. These include ensuring that the welding power source is calibrated to the torch positioner and other associated equipment and certifying that the positioner equipment performs repeatably to the equipment manufacturer's specifications. It is also imperative to verify that automation or robotic programs perform welding applications correctly and to substantiate the fixture's repeatability as well as its ability to hold the component to the print tolerance.

Robot integration entails the incorporation of additional quality disciplines into all upstream manufacturing processes. Users of robotic welding systems discover they must monitor many characteristics in the parts and process that may not have been significant prior to automation. The following factors should be examined carefully and thoroughly:

1. Subcomponent fabrication,
2. Workpiece fitup,
3. Weld process parameters,
4. Assembly sequence,
5. Material handling,
6. Quality requirements of the finished weldment,
7. Repeatability of joint location,
8. Allowable distortion, and
9. Production requirements.

PROCUREMENT SCHEDULING

Depending on the application, the installation of automated welding equipment can require several months. If a turnkey system is purchased, a schedule is usually part of the package; nonetheless, the responsibilities for the project are sometimes divided up between the buyer and the seller. Figure 11.20 presents a sample Gantt chart outlining the various steps and considerations involved in installing a turnkey welding system.

Phase I of the installation project begins with the formulation of the desired automated or robotic welding concept. A team is formed to define the application and obtain bids from several vendors. The team puts together initial costs for the project and defines the business impact on the company. The next step involves pilot testing and evaluation. Actual products or prototypes are fabricated to determine the welding process and procedures. This is followed by additional testing to qualify the pilot sample. Robotic arc welding personnel should be tested and qualified concurrently. Completion of Phase I involves disassembling any tooling or fixturing used during pilot fabrication or testing as well as a complete review of the work accomplished to this point. Phase I culminates with a recommendation made by the team with respect to manufacturing, financial, and production impacts.

Phase II of the automation project involves ordering materials, purchasing equipment, and scheduling resources. The project team requires a great deal of support from the vendor of choice at this time. A detailed integration plan defining responsibilities for the project is drafted. The next step involves the actual building of the automated cell with the component layout.

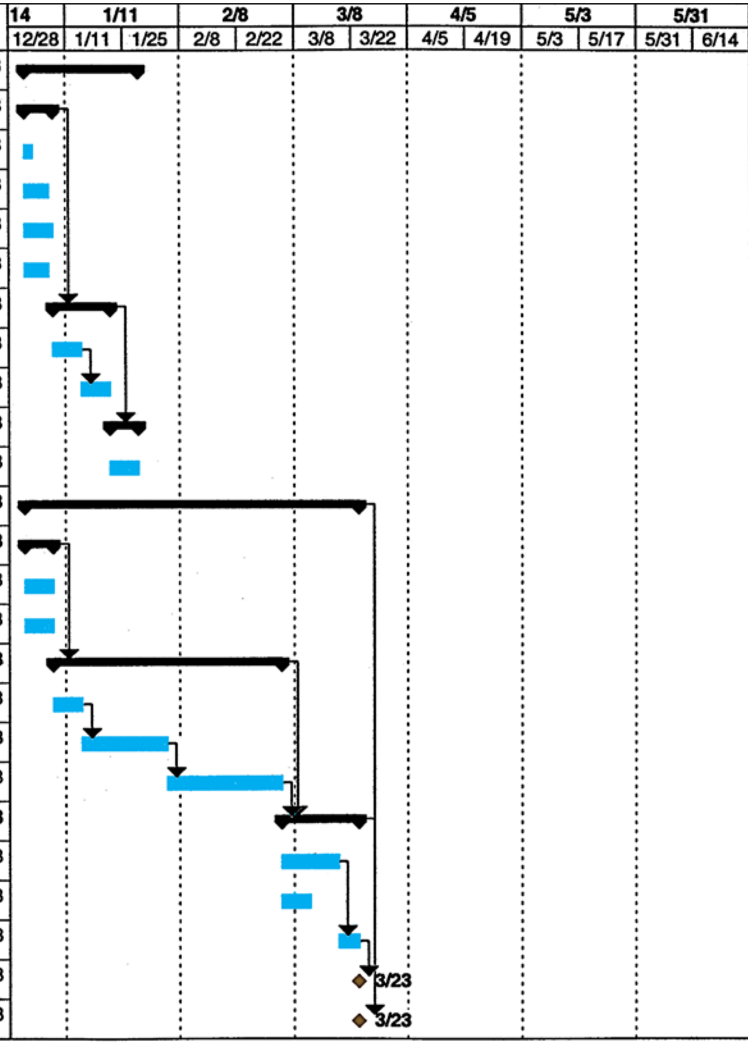
Required tooling and fixturing is fabricated and installed at this stage. Once all equipment is procured and installed, the automated system is tested. To this end, the electrical and systems components must be verified as functional. All procedures and specifications are established and documented, and quality assurance requirements are verified. After the testing is complete and the pilot samples are approved, the entire project is reviewed and evaluated based on actual information and results. This evaluation is conducted jointly by the project team and the vendor.

Phase III, which is not elaborated upon here, involves releasing the automation cell for production. The automation team and the vendor continue to work together to optimize the installation.

FACILITIES

The electrical power, air, and water supply requirements for automated or robotic welding equipment are typical of the machinery used in a fabrication shop.

ID		Task Name	Duration	Start
1		**PHASE I**	**20 days**	**Thu 1/1/98**
2		**Concepts Schedule**	**5 days**	**Thu 1/1/98**
3		Organize Manufacturing Team	2 days	Thu 1/1/98
4		Define Robotic or Automatic Application	4 days	Thu 1/1/98
5		Select Vendor or Systems Integrator	5 days	Thu 1/1/98
6		Estimate Financial and Business Impact	4 days	Thu 1/1/98
7		**Weld Sample Testing / Evaluation**	**10 days**	**Thu 1/8/98**
8		Welding Process Testing / Mock-ups	5 days	Thu 1/8/98
9		Destructive Testing and Qualification	5 days	Thu 1/15/98
10		**Go or No-Go Decisions**	**5 days**	**Thu 1/22/98**
11		Manufacturing and Financial Impact	5 days	Thu 1/22/98
12		**PHASE II**	**58 days**	**Thu 1/1/98**
13		**Procurement Schedule**	**5 days**	**Thu 1/1/98**
14		Capital Appropriations of Concept	5 days	Thu 1/1/98
15		Vendor or Systems Integrator Plan	5 days	Thu 1/1/98
16		**Automation Cell Construction**	**40 days**	**Thu 1/8/98**
17		Component Layout	5 days	Thu 1/8/98
18		Build Fixtures, Tooling and Prototypes	15 days	Thu 1/15/98
19		Installation of Equipment	20 days	Thu 2/5/98
20		**Automation Cell Testing**	**13 days**	**Thu 3/5/98**
21		Weld Pilot Testing (See Sample Testing)	10 days	Thu 3/5/98
22		Production Quality Review	5 days	Thu 3/5/98
23		Final Evaluations of Phase II	3 days	Thu 3/19/98
24		Phase II Complete	0 days	Mon 3/23/98
25		PHASE III - Release into Manufacturing	0 days	Mon 3/23/98



Project: Automation System Procurement

Task
Progress
Milestone
Summary
Rolled-Up Task
Rolled-Up Milestone
Rolled-Up Progress
External Tasks
Project Summary
Split
Rolled-Up Split

Page 1

Figure 11.20—Sample Gantt Chart of Installation Schedule

When cooling water is required, a recirculating cooling system is recommended to conserve water. In some applications, a closed-loop chiller may be beneficial in minimizing wire feed difficulty and extending torch life. A compressed air supply may require filters, dryers, or oilers.

When deciding where to locate an automated welding system, the area's safety clearances, arc radiation exposure, fume control, and susceptibility to spatter must be addressed. Lighting, temperature, humidity, cleanliness, vibration, noise, fumes, and smoke should also be considered. As automated welding applications require some human observation, working conditions in the area should ensure the operator's stable, reliable performance. Manufacturer specifications detailing equipment safety requirements should be enforced. Moreover, robot movement must not be impeded by possible collisions with material handling equipment, fixtures, hand tools, and other production equipment.

ENVIRONMENT

Proper quality control requires control of the welding environment. As atmospheric contamination can be destructive for electrical components, it is important to locate automated and robotic equipment in an area where the atmosphere can be controlled. If precautions are not taken, atmospheric contamination could give rise to safety and health concerns, affect mechanical accuracy, and shorten component life.

When harsh atmospheres are unavoidable, the equipment must be completely sealed or equipped with air-filtering devices. Regardless of the application, continued maintenance is needed to ensure a clean environment for the operator and the electrical components. Table 11.1 lists the factors that contribute to atmospheric contamination in the welding area.

Table 11.1
Common Atmospheric Contaminants

Dust, dirt, and other particles
Rust, corrosion, and salt air
Humidity and moisture
Residue from abrasive gears, bearings, and other mechanical devices
Magnetized shavings or dust
Residue from grinding operations
Welding fumes

SAFETY AND HEALTH

The operators of automated and robotic equipment can easily avoid jagged workpiece edges, moving conveyors, weld flash, and other welding hazards. However, the movement of the robot arm itself creates a hazardous environment. Thus, personnel must never be allowed to enter a robot's work envelope during production. Protective fences, power interlocks, and detection devices must be installed to ensure worker safety. Although the integration of automated and robotic welding systems reduces human exposure to fumes and other gases, the use of an appropriate exhaust system is highly recommended to remove fumes and gases from the welding area.

The topic of health and safety considerations related to robotic installations is addressed further in Chapter 17, "Safe Practices." In addition, the reader is advised to consult the *American National Standard for Industrial Robots and Robot Safety Systems—Safety Requirements*, ANSI/RIA R15.06.[20]

OPERATOR TRAINING AND EDUCATION

No matter how complex or simple an automated or robotic installation may be, training plays a vital part in its success. Operator training and education programs are essential components in planning for automation. Basic skills combined with practical experience form a solid foundation for all those involved with welding automation. Operators and other related personnel must possess a good background in the process being applied. A functional understanding of welding equipment, peripheral equipment, and maintenance requirements for cell components is necessary. Safety circuits and the control logic of flexible automation must be fully understood.

Though a great deal of training occurs on the job, structured and regular training is required with respect to system programming. Technicians involved with flexible automation must understand all of its documentation, including weld procedures, weld cell operation, and weld troubleshooting. Personnel must be cognizant of the mechanical capabilities of the robot's arm. An overview of recommended training requirements is presented in Table 11.2.

Documentation for automated equipment should establish long-term equipment and production measurements. Documentation also should include equipment manuals, procedures, and graphical information that support system operation and maintenance. A system of numbering, filing, revising, and maintaining operating programs is required for robots.

20. See Reference 17.

Table 11.2
Recommended Areas of Training for Operators of Automated and Robotic Welding Installations

Welding Technology
Manual welding (bead profile, penetration, number of passes, etc.)
Welding equipment (power supply, wire feeder, interface)
Welding codes and standards
Welding procedures and qualification tests
Use of consumables (wire, gas, torch parts, etc.)
Base and filler metals
Inspection and Quality Control
Weld discontinuities
Visual, radiographic, liquid penetrant, and other nondestructive examination techniques
Macro-sections, bend samples, and other destructive tests
Process capability review
Statistical evaluation (pieces/hour, costing, joint repeatability, etc.)
Use of Automated/Robotic Equipment
Mechanical and electrical operations
Safety barriers and circuits
Peripherals (torch cleaner, tool changers, etc.)
Cell or system layout
Troubleshooting
Programming and Computer Technology
Computer numerical control (CNC)
Computer-aided design (CAD)
Computer-aided manufacturing (CAM)
Programmable logic control (PLC) and other control systems
Networks, personal computers, and hardware nomenclature
System Maintenance
Mechanical aptitude
Electrical circuits
Cooling, air filtration, and other systems
Scheduled service plan
Fixturing and Tooling
Relationship of the tool center points to the fixture
Calibration to the drawing or specification

Investment

As the cost of designing and building an automated or robotic system is inherently high, this cost must be justified by determining that the system will be more economical. A cost justification analysis should be performed for potential welding automation projects. Various measurement techniques are used to evaluate the investment and payback period, including return on investment (ROI), return on assets (ROA), return on equipment (ROE), payback period, internal rate of return (IROR), and net present value (NPV).

Return on investment is calculated by dividing the net income by the investment. Some of the variables considered in an ROI equation include the average total assets for the last two years, stockholders' equity, and invested capital. The higher the ratio, the more desirable is the investment.

Factors that impact the return portion of the ratio include consistent quality; reduced variable welding costs; predictable welding production rates; ability to integrate with other automated operations; and increased productivity as a result of increased welding speeds, filler metal deposition rates, and increased arc-on time (efficiency). Factors that influence the investment portion of the ratio include acquisition of the automated or robotic equipment, tooling and fixturing, support equipment, and required upstream or downstream process upgrades.

The calculation of the payback period is the method that is the most commonly used to justify an automation project to upper management. This method is simple to use and easy to understand. A simple payback method might include these variables in the following formula:

$$P = \frac{I}{L - E} \tag{11.1}$$

where

P = Payback,
I = Investment,
E = Expense of automation,
L = Savings (derived from reduced labor costs, quality enhancement, and so forth).

Some companies have policies specifying that only projects with a three-year payback or better should be considered.

Changeover Time and Inventories

Frequent changeovers affect the production levels recorded by an automated cell, especially when different fixturing is needed. To optimize cell utilization, fixture placement must be kept accurate and efficient. The appropriate use of changeovers increases overall efficiency by supporting various production requirements, such as just-in-time inventories. Flexible welding automation can generate considerable savings by increasing inventory turnover. This reduces work-in-process and finished-goods inventory, which, in turn, saves money and space.

Floor Space

Plant floor space plays a role in product costs. The amount of floor space needed for an operation can often be reduced by implementing a cell concept. Product flow to and from the cell is as important as the area the cell occupies. Automating an operation necessitates the efficient flow of materials, whereas inefficiencies can sometimes be overlooked in a manual operation.

Personnel Requirements

Welding shops are often limited with respect to the availability of skilled personnel. Skilled welders are in high demand and receive relatively high pay. However, automated and robotic welding equipment can be operated by workers who are only partially skilled as long as personnel trained in the technology and process are available to maintain quality and production up time. Automation can also reduce the number of workers needed in a cell, leading to decreased labor costs.

Table 11.3
Recommended Maintenance for Arc Welding Equipment

Monthly or Weekly
Inspect and adjust wire feeder roll tension if necessary
Inspect or replace wire liner
Replace damaged or worn welding cables
Repair or replace leaking air or water lines
Replace leaking or damaged air or gas system regulators
Daily
Inspect electrical cables for shorts
Tighten loose bolts
Inspect for gas or water leaks
Clean the robot surroundings and air filters
Report maintenance findings to supervisor
Hourly or after a specific number of welds
Replace worn contact tips
Replenish wire supply
Check torch tool center point (TCP) and adjust if necessary

MAINTENANCE

In addition to maintaining the automated or robotic equipment according to the manufacturer's recommendations, periodic maintenance of the welding equipment must also be scheduled. Table 11.3 offers general guidelines for the periodic maintenance of arc welding equipment.

QUALITY CONTROL

Enhanced quality control is an important benefit of automation, with weld quality being dependent upon both motion control and process control. With appropriate feedback controls and regular maintenance, an automated welding machine can consistently maintain good weld quality.

In manual welding, an operator can easily misalign the welding torch or vary the welding speed, resulting in unacceptable weld quality. However, welding robots can be programmed to position the torch with the appropriate orientation to the weld joint and travel at the optimum speed. When different joint types exist on the same weldment, the robot can be programmed to use different welding schedules for each. Once the optimum welding conditions are developed and the automated system is programmed, consistently high weld quality can be achieved.

Automation offers the potential advantage of excellent performance every minute of every day. However, this is possible only if all of the inputs to the system are consistent and the equipment is properly maintained. Automated welding reduces defects, which can improve product performance under fatigue, brittle fracture, and corrosion conditions. Fewer repairs are required, and the scrap rate is reduced.

Among the many variables that can affect the quality of welds produced automatically are:

1. Material variations, including thickness, geometry, workpiece fitup, composition, and surface finish;
2. Welding or machine setting such as voltage, current, and gas flow rates;
3. Fixturing, including the repeatability of joint location, chill bars, and materials;
4. Procedures, such as alignment and preheat;
5. Consumables, including filler metals and gases;
6. Machine design and operation (e.g., bearings, guides, and gear trains);
7. Repeatability of the welding torch position; and
8. Fixture position repeatability.

Establishing and quantifying the baseline capabilities of each system component before initiating production can help maintain good quality control. Comparison with baseline data helps pinpoint problems during production. When the preproduction baseline capability of the welding robot, tooling, positioner, and welding equipment is quantified, it is relatively simple to determine the cause of production problems. For example, if the weld is suddenly being located incorrectly, the repeatability of each component can be compared to its respective baseline to determine the root cause. If baselines have not been established, the root cause can be determined only through trial and error.

CONCLUSION

Mechanized, automated, and robotic welding equipment will continue to become more reliable and cost-effective. New developments in sensors and user interfaces will result in the higher quality welds required by industry. Arc welding technology is the fastest-growing robotic welding equipment segment. Considering that over 90% of small-to-medium sized manufacturing concerns have yet to install robots, this segment has great potential.

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21. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

SUPPLEMENTARY READING LIST

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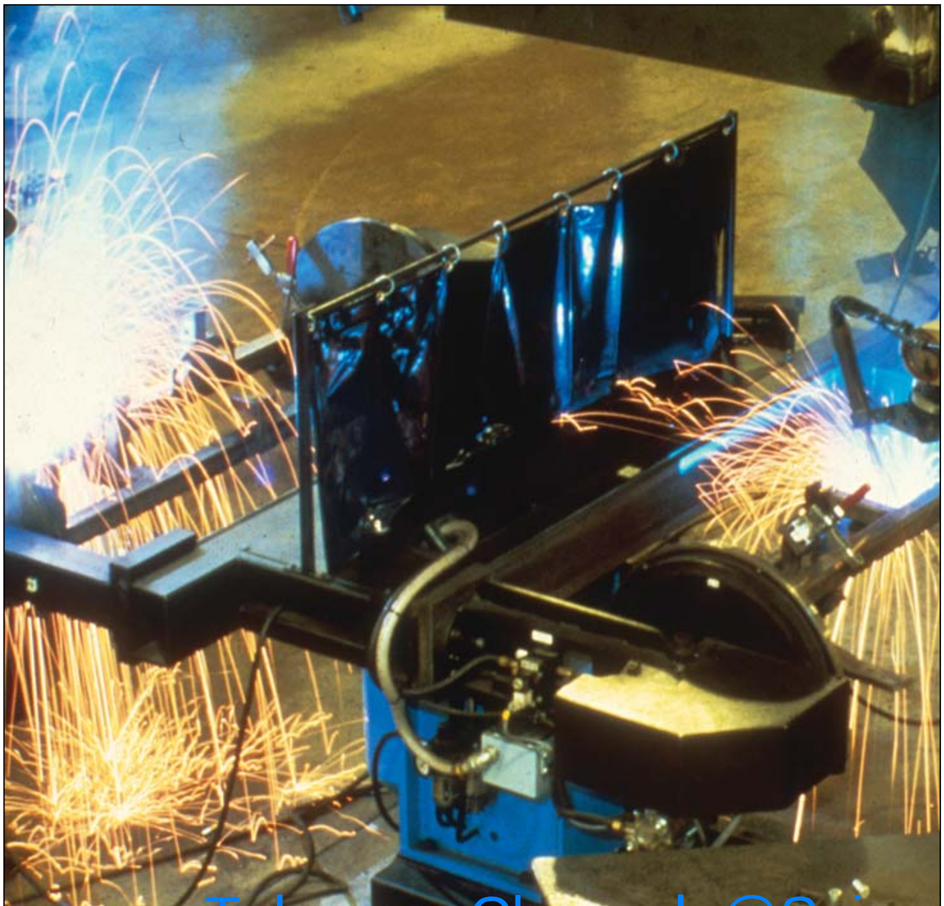
CHAPTER 12

ECONOMICS OF WELDING AND CUTTING



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Contents

CHAPTER 12

ECONOMICS OF WELDING AND CUTTING

INTRODUCTION

The success of a business is usually measured by its profitability, based on the ability of the company to hold costs to the limits defined by competitive selling prices. The costs associated with welding and related processes can readily be approximated for any job when the factors affecting those costs are known and appropriate estimating methods are used. Welding costs must be accurately determined if the estimate is to be used successfully for bidding, for setting prices, or for comparing welded construction to a competing process.

The cost elements of a product are those related to materials, labor, and overhead. Only welding materials such as filler metals, gases, and fluxes are considered in the chapter, and only the labor directly involved in welding is specifically addressed. Thus, information related to base metal costs as well as layout, forming, fitting, and other metalworking is not included. Overhead costs are not addressed in detail in this chapter because the amount of overhead varies from industry to industry, and the method of distributing overhead costs also varies.

To facilitate the development of welding cost standards, factual information and guidance that can be adapted to suit individual enterprises are presented. Because of the importance of cost estimation for automated systems, detailed information is provided on methods of estimating cycle time in the production of weldments by means of automated arc welding and resistance spot welding. A cost model developed to estimate the manufacturing costs specifically for resistance spot welding is described in detail.

Many of the procedures employed to estimate welding costs can be adapted to estimate brazing, soldering, and thermal spraying costs, as the processes are similar in many respects. Information specific to these processes is presented in the sections "Economics of Brazing and Soldering" and "Economics of Thermal Spraying."

To extend the usefulness of this information and enable its application to a wide variety of industries, material cost units are stated in pounds (lb) (kilograms [kg]) and cubic feet (ft^3) (cubic meters [m^3]), and labor cost units are stated in worker-hours (h). Users can convert the cost units to the dollar or other currency values by applying the cost of consumables and their specific labor and overhead rates.

THE COST ESTIMATE

A cost estimate is a forecast of expenses that may be incurred in the manufacture of products or components or in the implementation of new processes or operations. In addition to manufacturing costs, a typical cost estimate includes administrative, handling, warehousing, and storage expenses as well as data related to profit. Data derived from an accurate cost estimate can contribute to management decisions such as the following:

1. Establishing the selling price of a product for quotation purposes and for bidding and evaluating contracts;
2. Ascertaining whether a proposed product can be made and marketed at a profit, considering existing prices and anticipated competition;
3. Determining whether parts and assemblies should be fabricated in-house or purchased from a vendor;
4. Determining the amount of investment required for the acquisition of the tools and equipment needed to produce a product or a component using one process as compared to another;

5. Choosing the best and most economical method, process, and materials to manufacture the product;
6. Establishing a basis for a cost reduction program by demonstrating savings that are being realized or that could be realized by changing methods or processes or by applying value-analysis techniques;
7. Predetermining standards of production performance that can be used at the start of production to control operating costs; and
8. Predicting the effects of production volume changes on future profits as a result of the introduction of automation, mechanization, or other improvements suitable to mass production.

If production involves a new product, the details of the cost estimate should include the first formal process planning. This process planning may subsequently become the basis for the following decisions:

1. Establishing personnel requirements to meet future work plans;
2. Predicting material needs over the length of a contract;
3. Setting the overall schedule or timetable for meeting company goals; and
4. Specifying the equipment, machines, and facilities required for the production of a proposed product in the quantities required and within the time limitations.

ECONOMICS OF WELDING

All expenses that may be incurred by the company must be considered when preparing a cost estimate or establishing a selling price for a product. The accounting department often establishes general and administrative expenses, while management usually establishes the expected amount of profit. If the product to be manufactured includes weldments or brazements, the procedures for costing these must fit into the general accounting practices of the enterprise. Thus, only the manufacturing costs are of prime interest to the cost estimator.

Manufacturing costs include (1) direct materials, (2) direct labor, (3) expendable equipment, and (4) factory overhead (sometimes referred to as *burden*). Direct materials are the product components that become part of the finished product. They can easily be traced to the product in terms of units and materials consumed per product manufactured. Direct materials include those whose cost per unit can accurately be estimated.

Direct labor is work that is required for the production of a finished article. These costs, which may include the work involved in the performance of testing and inspection activities, can readily be charged to the finished product. Expendable equipment includes the small tools, fixtures, and accessories used in the production processes that are expendable and readily charged to the product.

Factory overhead consists of all indirect labor, materials, and other indirect manufacturing expenses[1] that cannot be allocated precisely to a product on a per-part basis. Allocations for facilities, equipment, power, air, utilities, and manufacturing services such as maintenance may be a part of these costs. Overhead costs can also be allocated to a product based on cost drivers such as direct labor hours or equipment hours. A portion of overhead costs may be fixed, while the remainder might vary depending upon the production rate, which is defined as the number of parts produced per unit of time.

ESTIMATING WELDING COSTS

Costs for welding include the basic elements common to other manufacturing processes and activities. In welding, however, these elements have many variables, some of which are unique to a welding process, while others may be proprietary to a company. Defining these variables requires the knowledge and experience of individuals familiar with the disciplines of engineering, metallurgy, manufacturing, and quality control.

The variables generally considered when estimating the costs of arc welding are listed in Table 12.1.

Computerization and data processing are important tools used in the determination of costs. Gathering and evaluating data for welding cost estimates can be an expensive and cumbersome chore; however, using computers and the appropriate application software, quick and convenient analyses of many welding variables can be produced. For example, database systems have been developed for the management of welding procedures and welder performance qualifications, production welding, and quality control.[2]

The welding procedure specification (WPS) provides important data needed to calculate the cost of the weld. Thus, the welding procedure specification can serve as the starting point for a cost estimate for welding, as it defines the welding variables to be used in the manufacturing process and provides a basis for repeatability and consistency in production. Many companies have

1. Indirect costs are those expenses and labor charges that are necessary to support production but are not directly attributable to value-added operations.
2. Brightmore, A. D., and M. Bernasek, 2000, Moving Weld Management from the Desk to the Desktop, *Welding Journal* 79(1): 43–45.

Table 12.1
Typical Variables Used in the Estimation of Welding Costs for the Arc Welding Processes

Cycle time
Electrode or filler wire
Size
Type
Electrode deposition efficiency
Type of joint
Type of weld
Weld size
Type of shielding
Shielding gas flow rate
Flux consumption ratio
Welding current
Arc voltage
Power source efficiency
Welding time
Operator factor
Labor rates
Overhead rate
Filler metal cost
Shielding gas cost
Setup costs
Inspection costs

standardized welding procedures that are used for various jobs of a similar nature. A sample welding procedure specification form indicating the variables to be used for a given job is shown in Figure 12.1.

Materials Estimate

Material costs are comprised of the cost of those materials consumed in the workplace while making the weld. For welding processes in which filler metal is deposited, the amount of deposited metal can be the basis for all material costs. The total cost per pound (kilogram) of filler metal deposited is commonly used in estimates in place of cost per worker-hour.

Other material costs include process-specific items such as gases, fluxes, backing rings or strips, and anti-spatter compounds. Gases include those required for shielding in arc welding and brazing operations and those used for fuel and oxygen in oxyfuel gas welding, brazing, and soldering. Fluxes include those used in submerged arc and electroslag welding and in brazing and soldering operations.

The quantity of consumable materials required and the number of tasks necessary to complete production of the item are fundamental to a cost estimate. Labor hours can be estimated from an accurate list of materials and a summary of the operations required for the production of each piece. Many fabricators develop standard manufacturing practices so that the labor allowances can be determined directly from the material requirements.

Bill of Materials. To prepare a welding cost estimate, the estimator needs a list of each weld in the assembly, including the weld type, size, and length, and a list of all of the materials required to produce the welds.

For enterprises that produce a small range of similar products with a few standard manufacturing practices, less judgment is required of the estimator to prepare a bill of materials and to convert the materials requirements to a labor estimate. However, for custom fabricators that produce a large variety of products, the estimator must be aware of the specific procedures that are followed in the shop. For each product fabricated, the estimator must forecast whether the efficiencies normally achieved in the shop procedures will be achieved. If it is anticipated that normal efficiencies cannot be achieved, the estimator must calculate different values based on the simplicity or complexity of the work.

When the material estimate is prepared and a welding procedure and joint geometry are assigned to each weld, the weight of deposited filler metal per foot (meter) of weld can be estimated from charts such as those shown in Tables 12.2 through 12.10. The densities of various common metals and alloys are presented in Table 12.10.

Although the data presented in the tables are for steel, these data can be used to determine the weight of any deposited metal. Calculations can be made according to the following equation:

$$W = \rho DV \tag{12.1}$$

where

W = Weight of the deposited metal in question, lb/ft (kg/m);
ρ = Density of the deposited metal, lb/in.^{3} (g/mm^3); and
DV = Deposited metal volume, in.^{3}/ft (mm^3/mm) from Tables 12.2 through 12.10.

The weight of the deposited weld metal is required in the determination of all arc welding costs other than autogenous processes. The welding process and the welding procedure affect the quantity of filler metal, flux, gas, and labor required for fabricating each weldment. All of these quantities can be derived from the deposited metal weight.

WELDING PROCEDURE SPECIFICATION

Company Name
Welding Process(es)
Supporting PQR No.(s)

WPS#
Rev Date By
Type: Manual Machine Semi Automatic Automatic

JOINT DESIGN USED
Type:
Single Weld Double Weld
Backing: Yes No

Backing Material:
Root Opening: Root Face:
Groove Angle: Radius (J-U):
Back Gouging:

POSITION
Groove: Fillet:
Vertical Progression:

ELECTRICAL CHARACTERISTICS
Transfer Mode (GMAW)
Current AC DCEN DCEP
Other
Tungsten Electrode (GTAW)

BASE METALS
Material Specification:
Type or Grade:
Thickness: Groove Fillet

FILLER METALS
AWS Specification
AWS Classification

TECHNIQUE
Bead: String Weave
Pass: Multiple Single
Number of Electrodes:
Electrode Spacing Longitudinal Lateral

Contact Tube to Work Distance:
Peening:
Interpass Cleaning:

SHIELDING
Flux: Electrode/Flux Class

Gas: Composition:
Flow Rate: Gas Cup Size:

POST WELD HEAT TREATMENT
Temperature:
Time:

PREHEAT
Preheat Temperature, Minimum:

Interpass Temperature, maximum

Pass or Layers	Process	Filler Metals Class	Filler Metals Dia.	Current Type	Current Amps	Volts	Travel Speed	Joint Details

We, the undersigned, certify that this Welding Procedure Specification meets the requirements of AWS D1.1:1998.

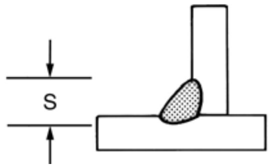
Company ______________________________

By ____________________________ Date __________________

Source: American Welding Society (AWS), 1999, *Design and Planning Manual for Cost-Effective Welding*, Miami: American Welding Society, Figure 14.1.

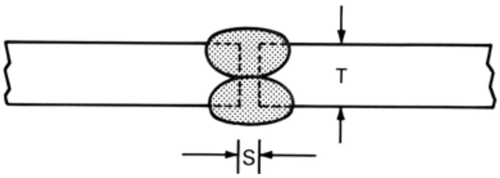
Figure 12.1—Sample Welding Procedure Specification Form

Table 12.2
Volume and Weight of Steel Fillet Welds



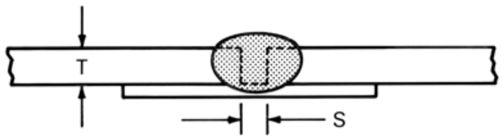
Fillet Weld Size, S		Deposited Metal			
		Volume		Weight	
in.	mm	$in.^3/ft$	mm^3/mm	lb/ft	kg/m
3/16	5	0.34	18.2	0.10	0.15
1/4	6	0.43	21.1	0.12	0.18
5/16	8	0.68	36.6	0.19	0.28
3/8	10	0.96	51.2	0.27	0.40
7/16	11	1.3	69.9	0.36	0.54
1/2	13	1.7	91.4	0.48	0.71
5/8	16	2.5	134.4	0.71	1.06
3/4	19	3.6	193.6	1.0	1.5
7/8	22	5.0	268.8	1.4	2.1
1	25	6.4	344.1	1.8	2.9

Table 12.3
Volume and Weight of Square-Groove Butt Joints in Steel, Welded Both Sides



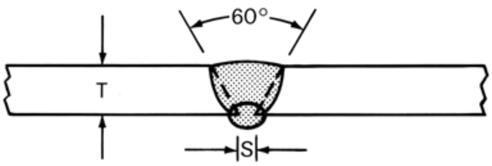
Joint Dimensions				Deposited Metal			
Thickness, T		Size, S		Volume		Weight	
in.	mm	in.	mm	$in.^3/ft$	mm^3/mm	lb/ft	kg/m
1/8	3.2	0	0	0.43	23.1	0.12	0.18
		1/32	0.8	0.46	24.7	0.13	0.19
3/16	4.8	1/32	0.8	0.71	38.2	0.20	0.29
		1/16	1.6	0.79	42.5	0.22	0.33
1/4	6.4	1/16	1.6	0.93	50.0	0.26	0.39
		3/32	2.4	1.0	53.8	0.29	0.43

Table 12.4
Volume and Weight of Square-Groove Butt Joints in Steel with Backing Strip



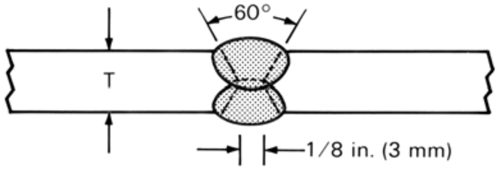
Joint Dimensions				Deposited Metal			
Thickness, T		Size, S		Volume		Weight	
in.	mm	in.	mm	in.^{3}/ft	mm^3/mm	lb/ft	kg/m
1/8	3.2	0	0	0.22	11.8	0.06	0.09
		1/16	1.6	0.32	17.2	0.09	0.13
3/16	4.8	0	0	0.33	17.7	0.09	0.14
		3/32	2.4	0.53	28.5	0.15	0.22
1/4	6.4	0	0	0.45	24.2	0.13	0.19
		1/8	3.2	0.75	40.3	0.21	0.31

Table 12.5
Volume and Weight of Single-V-Groove Butt Joints in Steel with a Back Weld



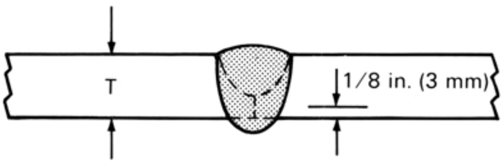
Joint Dimensions				Deposited Metal			
Thickness, T		Size, S		Volume		Weight	
in.	mm	in.	mm	in.^{3}/ft	mm^3/mm	lb/ft	kg/m
1/4	6	1/16	2	0.81	43.5	0.23	0.34
5/16	8	3/32	2	1.2	64.5	0.35	0.52
3/8	10	1/8	3	2.0	10.8	0.57	0.85
1/2	13	1/8	3	3.5	18.8	1.0	1.5
5/8	16	1/8	3	4.8	25.8	1.4	2.1
3/4	19	1/8	3	5.7	30.6	1.6	2.4
1	25	1/8	3	10.0	53.8	2.8	4.2

Table 12.6
Volume and Weight of Double-V-Groove Joints in Steel



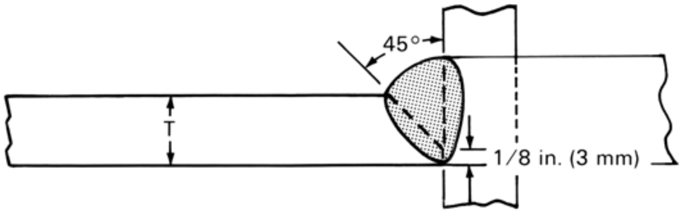
Joint Dimensions		Deposited Metal			
Thickness, T		Volume		Weight	
in.	mm	in.^{3}/ft	mm^3/mm	lb/ft	kg/m
5/8	16	3.0	160	0.86	1.3
3/4	19	3.9	210	1.1	1.6
1	25	6.0	320	1.7	2.5
1-1/4	32	8.5	460	2.4	3.6
1-1/2	38	11.5	620	3.3	4.9
1-3/4	44	14.9	800	4.2	6.2
2	50	18.8	1000	5.3	7.9
2-1/4	57	23.0	1240	6.5	9.7
2-1/2	64	27.8	1500	7.9	11.8
3	75	38.5	2070	10.9	16.2

Table 12.7
Volume and Weight of Single-U-Groove Butt Joints in Steel



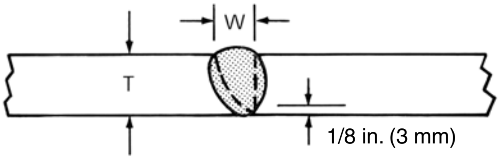
Joint Dimensions		Deposited Metal			
Thickness, T		Volume		Weight	
in.	mm	in.^{3}/ft	mm^3/mm	lb/ft	kg/m
1/2	13	3.0	160	0.84	1.3
5/8	16	3.9	210	1.1	1.6
3/4	19	5.4	290	1.5	2.2
1	25	7.9	420	2.2	3.3
1-1/4	32	10.7	580	3.0	4.5
1-1/2	38	13.9	750	3.9	5.8
1-3/4	44	17.1	910	4.8	7.1
2	50	20.0	1070	6.0	8.3
2-1/4	57	25.4	1370	7.1	10.6
2-1/2	64	30.0	1610	8.4	12.5
2-3/4	70	34.6	1860	9.7	14.4
3	75	40.0	2150	11.2	16.2
3-1/2	89	51.1	2750	14.3	21.2
4	100	63.9	3450	17.9	26.6

Table 12.8
Volume and Weight of Single-Bevel Groove Joints in Steel



Joint Dimensions		Deposited Metal			
Thickness, T		Volume		Weight	
in.	mm	in.^{3}/ft	mm^3/mm	lb/ft	kg/m
1/4	6	0.21	11.3	0.06	0.09
5/16	8	0.39	21.0	0.11	0.16
3/8	10	0.61	32.8	0.17	0.25
1/2	13	1.2	64.5	0.34	0.51
5/8	16	2.0	108	0.56	0.83
3/4	19	3.0	160	0.84	1.25
1	25	5.7	310	1.6	2.4

Table 12.9
Volume and Weight of Single-J-Groove Joints in Steel



Joint Dimensions		Deposited Metal			
Thickness, T		Volume		Weight	
in.	mm	in.^{3}/ft	mm^3/mm	lb/ft	kg/m
1	25	5.7	310	1.6	2.4
1-1/4	32	7.9	420	2.2	3.3
1-1/2	38	10.4	560	2.9	4.3
1-3/4	44	13.2	710	3.7	5.5
2	50	15.7	840	4.4	6.5
2-1/4	57	18.6	1000	5.2	7.7
2-1/2	64	22.1	1190	6.2	9.2
2-3/4	70	25.7	1380	7.2	10.7
3	75	29.6	1590	8.3	12.4
3-1/2	89	38.2	2050	10.7	15.9
4	100	47.5	2550	13.3	19.8

Table 12.10
Approximate Density for Some Common Engineering Alloys

	Density	
Alloy Group	**lb/in.^{3}**	**g/mm^3**
Carbon steel	0.28	7.8×10^3
Stainless steels	0.29	8.0×10^3
Copper alloys	0.31	8.6×10^3
Nickel alloys	0.31	8.6×10^3
Aluminum alloys	0.10	2.8×10^3
Magnesium alloys	0.065	1.8×10^3
Titanium alloys	0.17	4.7×10^3

LIVE GRAPH
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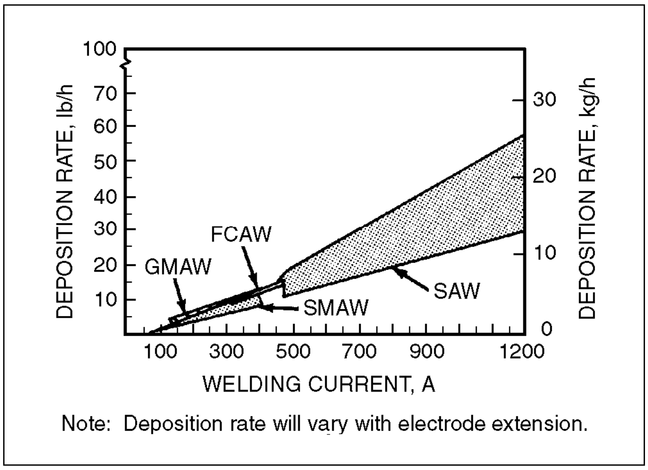

Figure12.2—Effect of Welding Process and Welding Current on the Deposition Rate

To determine the quantities of filler metal, gas, flux, and labor based on the weight of the deposited metal, the estimator must know the filler metal deposition rate, the deposition efficiency, and the operator factor—the ratio of arc time to the total work time needed to complete a weld.

Filler Metal Deposition Rate. The deposition rate is the weight of filler metal deposited per unit of arc-on time. The amount of filler metal required depends on the deposition efficiency (see below) and the deposited metal. The weight of filler metal required for each weldment can be calculated using the following equation:

$$FM = \frac{100\,(DW)(L)}{DE} \tag{12.2}$$

where

FM = Weight of filler metal, lb (kg);
DW = Deposited metal, lb/ft (kg/m);
L = Weld length, ft (m); and
DE = Deposition efficiency, %.

Typical deposition rates for the welding of steel by means of several consumable electrode processes as a function of welding current are shown in Figure 12.2

Figure 12.3 demonstrates the effect of welding current in amperes (A) and covered electrode classification on the deposition rate.

Approximate deposition rates for several welding processes are shown in Figures 12.4 through 12.6.

Filler Metal Deposition Efficiency. The deposition efficiency, expressed as a percentage, is determined by calculating the ratio of the deposited metal weight to the weight of filler metal used. The efficiency of deposition decreases as a result of losses incurred in the disposal of the stub ends of electrodes, metal vaporization in the arc, the conversion to slag of core wire components, and weld spatter.

Typical deposition efficiencies for several welding processes and electrodes are presented in Table 12.11. Table 12.12 presents information that can be used to estimate the weight of filler metal per weld inch (millimeter) for bare electrode wire of various American Welding Society (AWS) classifications. The data presented in Table 12.13 can be used to estimate inches per pound (in./lb) (m/kg) of filler metal using steel flux cored arc electrodes.

Supplementary Requirements for Welding Consumables. The shielded metal arc welding (SMAW) and self-shielded flux cored arc welding (FCAW-S) processes do not require additional consumable supplies. However, submerged arc welding (SAW) requires a flux, and gas metal arc welding (GMAW) and gas shielded flux cored arc welding (FCAW-G) require a shielding gas. Although flux consumption varies, the average value of a pound (kilogram) of flux per pound (kilogram) of filler metal is an accepted amount.

Users should analyze their results to determine the appropriate flux consumption. Gas consumption for gas metal arc and flux cored arc welding is approximately 10 to 15 ft^3/(100 A)(h) [0.28 to 0.42 m^3/(100 A)(h)] depending on the gas, equipment and other local conditions. A sample calculation of shielding gases required to deposit 300 lb (136 kg) of filler metal is shown in Table 12.14.

LIVE GRAPH
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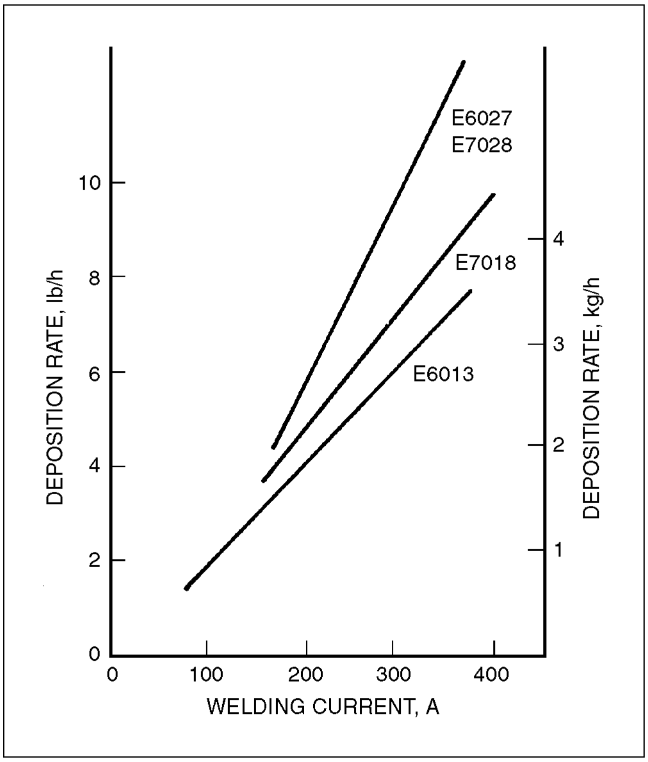

Figure12.3—Effect of Welding Current (A) and Covered Electrode Classification on the Deposition Rate

LIVE GRAPH
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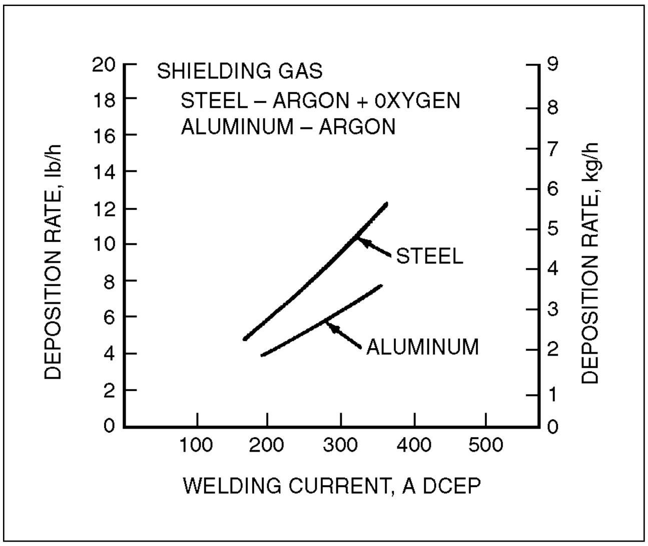

Figure 12.4—Effect of Welding Current (A, DECP) on the Deposition Rates of 1/16 Diameter Steel and Aluminum GMAW Welding Wires

LIVE GRAPH
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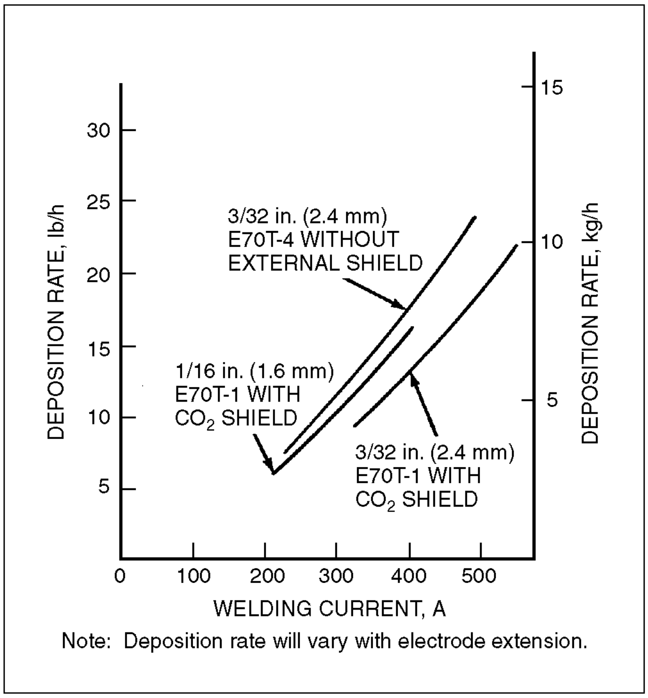


Figure 12.5—Effect of Welding Current (A) on Deposition Rates of 1/16 (1.6 mm) and 3/32 (2.4 mm) Diameter Steel Welding Electrodes for the Flux Cored Arc Welding Process

LIVE GRAPH
Click here to view

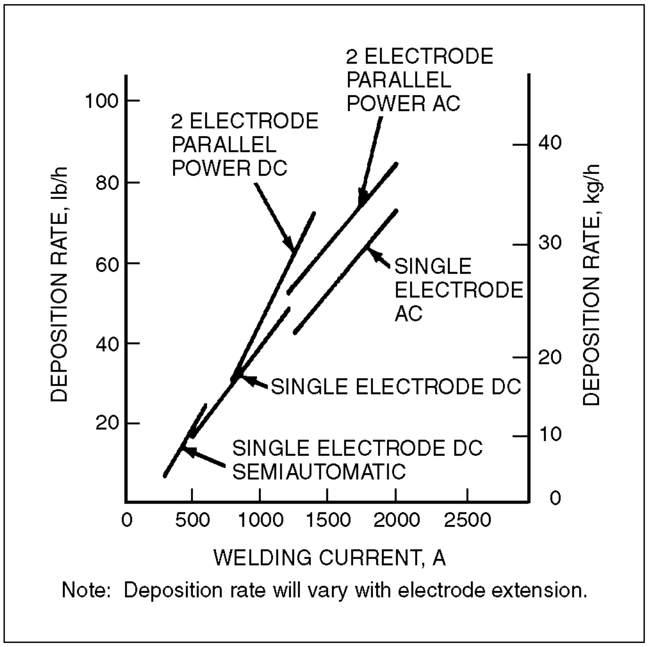


Figure 12.6—Effect of Welding Current (A) on the Deposition Rate of Submerged Arc Welding

Table 12.11
Deposition Efficiency for Welding Processes and Filler Metals

Filler Metal Form and Process	Deposition Efficiency,%*
Covered electrodes (SMAW)	
14 in. (35.5 mm)	55 to 65
18 in. (45.7 mm)	60 to 70
28 in. (71.1 mm)	65 to 75
Flux cored electrodes (FCAW)	80 to 90
Bare solid wire	
Submerged arc welding (SAW)	95 to 99
Gas metal arc welding (GMAW)	90 to 97

*Includes stub loss.

Table 12.12
Length per Unit Weight, Bare Electrode Wire of Various AWS Classifications (in./lb [mm/kg])

Diameter in. (mm)	ER-1100 (A1)	ERCuA1-AX (CU-A-1)	ERCu (Cu)	ERCuSi-A (CuSi)	ERCuNi (Cu-Ni)	ERAZXXA (Mg-Zn)	ERNi-1 (Ni)	ER70S-X (Steel)	ER3XX (Sst)
0.020 (0.51)	32400	11600	10300	9800	9950	50500	9900	11100	10950
0.025 (0.63)	22300	7960	7100	6750	6820	34700	6820	7680	7550
0.030 (0.76)	14420	5150	4600	4360	4340	22400	4400	4960	4880
0.035 (0.89)	10600	3780	3380	3200	3260	16500	3240	3650	3590
0.040 (1.01)	8120	2900	2580	2450	2490	12600	2480	2790	2750
0.045 (1.14)	6410	1120	1070	1020	1040	5270	1030	1160	1140
0.078 (1.98)	2120	756	675	640	650	3300	647	730	718
0.093 (2.36)	1510	538	510	455	462	2350	460	519	510
0.125 (3.17)	825	295	263	249	253	1280	252	284	279
0.156 (3.96)	530	189	169	160	163	825	162	182	179
0.187 (4.75)	377	134	120	114	116	587	115	130	127
0.250 (6.35)	206	74	66	62	64	320	63	71	70

Table 12.13
Inches per Pound (kg/mm) of Steel Flux Cored Electrode

Electrode Size			
in.	mm	in./lb	mm/kg
— (0.045)	1.143	2400	27 706
1/16 (0.062)	1.587	1250	14 430
5/64 (0.078)	1.984	1000	11 544
3/32 (0.094)	2.381	650	7 504
7/64 (0.109)	2.778	470	5 425
1/8 (0.125)	3.175	345	3 982

Table 12.14
Sample Calculation of Shielding Gas Requirements

Variable	Process GMAW	Process FCAW
Deposited weld metal required, lb (kg)*	300 (136)	300 (136)
Deposition rate, lb/h (kg/h)*	10 (4.5)	15 (6.8)
Arc time,† h	30	20
Gas flow rate,‡ ft^3/h (m^3/h)	40 (1)	40 (1)
Total shielding gas required, ft^3 (m^3)	1200 (30)	800 (20)

*Assumed for this example.
† The following expression is used to calculate the arc time:

$$\text{Arc time } (AT),\ h = \frac{\text{Deposited metal, lb (kg)}}{\text{Deposition rate, lb/h (kg/h)}}$$

‡ The following is used to calculate gas consumption:

$$\left[\text{Gas flow rate, ft}^3/\text{h (mm}^3/\text{h)}\right]\left[\begin{array}{l}\text{Arc time} \times \text{gas flow rate} = \\ \text{Total amount of gas consumed}\end{array}\right]$$

Gas consumption depends on the arc time, which is a function of deposition rate. Thus, the higher deposition rate of the flux cored arc process requires less shielding gas than the gas metal arc process.

The deposition rate is an important variable in welding economics. It is approximately dependent on the welding current regardless of welding process, as shown in Figure 12.2. The major differences in deposition rates with various welding processes are related to the usability of the processes at high welding currents. However, deposition rate is not the only factor in the choice of a welding process. Other factors include deposition efficiency, welding position, weld quality, required penetration, and the availability of equipment and qualified personnel.

Methods of improving deposition rates with a given process and factors affecting the choice of processes with higher deposition rates are discussed in the sections "Process Selection" and "Deposition Efficiency."

Labor Costs

Labor costs are based on the different amounts of time that it takes to perform all the tasks involved in the fabrication of a weldment. These different times include arc time, nonarc time, also referred to as *handling time*, and miscellaneous workplace time, the latter of which may involve such activities as joint preparation, testing, inspection, record keeping, and quality control.

The term *arc time* refers to the length time the arc is maintained while making a weld. Arc time depends on factors controlled by the power source and associated equipment, such as electrode or filler wire feed speed, arc voltage, and welding current, travel speed, type of welding power and polarity. Additional variables that affect arc time and the rate at which the weld is made include welding process, joint design, weld size, electrode type and size, and welding position.

Nonarc time, or handling time, is calculated for all of the workplace functions involving picking up the workpiece, placing it in a fixture, clamping and positioning it before and during welding, and finally moving the weldment to the next location. Nonarc time can be estimated with reasonable accuracy only for those operations that are repetitive. Because of the variations in time requirements for nonrepetitive tasks, the times required to realize these tasks are best included in the category *miscellaneous workplace time* (see below). Input from an industrial engineer may be needed when analyzing the time increments required to complete repetitive or nonrepetitive tasks.

Two methods can be employed to estimate the nonarc time required in an arc welding operation. One method utilizes an operator factor. Table 12.15 presents typical operator factor values for various welding methods. Once the operator factor has been determined (see below), the entire cost estimate becomes a function of the arc time. When using the operator factor, the labor time required to produce a weldment is calculated as follows:

$$h = \frac{AT}{\left(\frac{K}{100}\right)} \tag{12.3}$$

where

h = Labor time, h;
AT = Arc time, h;
K = Operator factor, %.

Table 12.15
Operator Factor for Various Welding Methods

Welding Method	Operator Factor Range, %
Manual	5 to 30
Mechanized	40 to 90
Semiautomatic	10 to 60
Automated	50 to 100

The other method involves analyzing the components, or inputs, of the nonarc time. For example, the inputs for calculating the nonarc time required to produce a weldment might be the following:

1. Setup time,
2. Number of detailed parts to be loaded,
3. Average time required to load a part,
4. Tack weld time,
5. Number of welds,
6. Time required to move from weld to weld,
7. Time required to adjust workpiece fit,
8. Time required to change consumables,
9. Time required to adjust equipment,
10. Time required for postweld finishing,
11. Inspection time, and
12. Time required for other activities related to the weld.

When explicitly calculating the nonarc time, the labor time is calculated as follows:

$$h = AT + N \tag{12.4}$$

where

h = Labor time, h;
AT = Arc time, h; and
N = Nonarc time, h.

When the nonarc time factors are evaluated, the cost estimate may point out the need for changes in procedure or for the use of additional equipment, such as fixturing, that can yield substantial reductions in weld cycle time.

Miscellaneous workplace time includes the many nonrepetitive, nonrecurring times that cannot be measured easily but must be cost-estimated. These include the time it takes to realize tasks such as stamping, applying antispatter compound, tack welding runoff tabs or backing strips in place, repositioning the workpiece between weld passes, and any variable time increment not directly involved in making the weld.

Joint preparation, record keeping, weld testing and inspection, and quality control are other cost considerations that may be included in this category. The labor, material, and other costs incurred in joint preparation must be included in the cost estimate. Joint preparation of the workpiece may involve machining, flame or plasma arc cutting, grinding, or bending. The most efficient and cost-effective method should be implemented, based on the requirements of the product design and the welding process.

Accountability records for welding procedures are often required in addition to records specifying contract provisions and fabrication procedures. The required records may include documentation of vendor certification of base materials and electrodes; compliance with specifications, applicable standards, or codes; the nondestructive examination of welds; welder or operator certifications; and quality control.

Operator Factor. The operator factor, used to determine labor costs, is a calculation of the ratio of arc time or actual weld deposition time to the total work time required of the welder or welding operator. The formula used to calculate operator time is presented in Equation (12.3).

Some typical ranges for the various methods of welding are shown in Table 12.15. Work sampling[3] is an effective approach for the collection of data used for the estimation of an operator factor. In assigning values to these variables, the estimator should use data based on shop experience. If such data are not available or the welding project is different from normal shop work, then the estimator should research the project and make an educated judgment for each factor.

Estimating Labor Hours. To determine the labor hours required for a particular task, the estimator should judge the complexity of the work. If the work involves either the frequent relocation of the welder or welding operator and the welding equipment or the repositioning of the workpieces, a low operator factor should be expected. When the welder or operator is required to perform fewer supplementary activities, the operator factor should be high because the welder or operator can accomplish more welding.

Labor is calculated as follows:

$$\text{Labor, h} = \frac{100 \times \text{Arc time } (AT)}{\text{Operator factor, \%}} \tag{12.5}$$

where

$$\text{Arc time } (AT),\ \text{h} = \frac{\text{Deposited weld metal, lb (kg)}}{\text{Deposition rate, lb/h (kg/h)}} \tag{12.6}$$

A sample calculation to determine the labor required to deposit 300 ft (90 m) of 1/4 in. (6 mm) fillet weld in the horizontal position using submerged arc welding (SAW) and flux cored arc welding (FCAW) is shown in Table 12.16. Both deposition rate and operator factor contribute to the labor estimate. This method can be used to estimate the labor required to weld any type of joint.

3. Pipe, E. S., 1992, Work Sampling, in *Handbook of Industrial Engineering*, G. Salvendy, ed. New York: John Wiley and Sons.

Table 12.16
Sample Calculation of Labor Hours Required for 300 ft (90 m) of Fillet Weld

Variable	SAW	FCAW
Weld size, in. (mm)	1/4 (6)	1/4 (6)
Weld length, ft (m)	300 (91)	300 (91)
Weight of deposited weld metal, lb (kg)*	36 (16)	36 (16)
Deposition rate, lb/h (kg/h)†	6 (2.7)	9 (4.1)
Operating factor, %‡	30	40
Labor, h§	20	10
Gas required, ft^3 (m^3)#	NA	160 (4.5)

*From Table 12.2.
† From Figures 12.3 and 12.5 and from the weld procedure (see Figure 12.6).
‡ From Table 12.15.
§ See Equations (12.5) and (12.6).
\# Gas required at 40 ft^3 (m^3) = Gas flow rate ft^3/h (m^3/h) × Arc time, h.
NA = Not available.

Standards Development. Many organizations have developed standard welding procedures to fabricate the welds frequently specified in their products. They have also determined the quantity of materials and labor required for the production of each type of weld. These standards can be used to estimate welding costs, measure shop production performance, and set production incentive standards.

Welding procedures provide data that can be used to develop production standards. These, in turn, can be used to accomplish the following:

1. Estimate welding costs;
2. Manage production planning;
3. Forecast personnel, inventory, and equipment requirements;
4. Justify new equipment;
5. Analyze job performance;
6. Manage cost-reduction programs; and
7. Set up incentive programs.

The fabricators of welded products should develop standard practices and procedures that include associated cost standards. Published values for the deposition rate, deposition efficiency, and operator factor can be used to develop these standards. However, it should be noted that published values are industry averages, which should be used only as starting values for the development of cost standards. These standards can then be refined by including the production costs for actual jobs. In fact, when using actual production costs, the standards developed can be expanded to include sawing, punching, fitting, and other metalworking standards.

A sample format for welding cost standards, including the data used for the calculations, is shown in Table 12.17. The data shown in Table 12.17 were developed in accordance with the procedures discussed in this section and incorporates information from Tables 12.4 and 12.5.

Table 12.17
Typical Welding Material and Labor Standards

				Submerged Arc*			Shielded Metal Arc*	
Joint Configuration	Plate Thickness, in.†	Root Opening, in.†	Deposited Metal Weight, lb/ft‡	Filler Metal Required, lb/ft‡	Flux Required, lb/ft‡	Labor Required, h/ft§	Filler Metal Required, lb/ft‡	Labor Required, h/ft§
Table 12.5	1/4	1/16	0.23	0.23	0.23	0.02	0.4	0.18
Table 12.5	1/2	1/8	1.0	1.0	1.0	0.07	1.5	0.8
Table 12.5	3/4	1/8	1.6	1.6	1.6	0.11	2.5	1.3
Table 12.4	1/8	1/16	0.09	0.09	0.09	0.012	0.14	0.072
Table 12.4	3/16	3/32	0.15	0.15	0.15	0.02	0.23	0.12
Table 12.4	1/4	1/8	0.21	0.21	0.21	0.028	0.32	0.17

Welding Process	Electrode Diameter, in.	Welding Current, A	Deposition Efficiency, %	Flux Ratio	Deposition Rate, lb/h	Operator Factor, %
Submerged arc	5/32	500	100	1	15	65
Shielded metal arc	7/32	350	65	NA	5	25

*Process data.
† To convert from in. to mm, multiply inches by 25.4.
‡ To convert from lb/ft to kg/m, multiply lb/ft by 1.49.
§ To convert from h/ft to h/m, multiply h/ft by 3.28.
NA = Not available.

ESTIMATING THE DIRECT COSTS OF ARC WELDING

The use of accurate values for estimates versus actual costs is a fundamental cost accounting principle. Estimates for quotations to customers are sometimes developed using outdated sketches and specifications, with minimal investigation into specific welding details of the project. The resulting quotation may be so inaccurate that the company loses the bid if it is too high or makes little or no profit if it is too low. Thus, the various cost factors of weldments required for a proposed project or product should be researched and verified to assure that actual costs are known.

A data breakdown of the actual weld time and the weight of deposited metal showing the cost per hour and per pound unit weight should be created and summarized for each weldment needed for the product. The final summary should contain figures representing the estimated costs, actual costs, and the difference between the two.

A cost summary provides data to aid in the following functions:

1. Validation of cost accounting for welded items,
2. Preparation of accurate cost estimates and submission of appropriate quotations,
3. Justification of purchases of welding and cutting equipment improvements,
4. Building the company's historical database and developing confidence in its use,
5. Contributing to the training of personnel involved in the weldment manufacturing and cost-summarizing processes, and
6. Improving communications between the various departments within a welding operation.

Table 12.18 presents the equations used for various cost estimations. It should be noted that although this table presents a method of estimating arc welding costs, the accuracy of the equations for every application cannot be guaranteed. Both the judgement of the estimator and the accuracy of input data influence the estimate. The arc welding cost terminology utilized in Table 12.18 is defined in Table 12.19.

Table 12.20 presents arc welding values for steel for five commonly used processes, showing deposition efficiency and operator factor averages expressed as a percentage, with estimated ranges for material costs.

OVERHEAD

Overhead includes such expenses as salaries and employee benefits, rent and depreciation of facilities, depreciation or lease costs, maintenance cost of the buildings and grounds, taxes, utilities, safety and fire equipment, and supporting services. Although overhead is a constituent of weldment costs, the expense for overhead is usually fixed by company management. The welding estimator, whose primary concern is weldment manufacturing costs, should consult management personnel for overhead allocations.

AUTOMATED AND ROBOTIC SYSTEMS

This section presents a general methodology for determining the cycle time to produce a weldment in various automated arc or resistance spot welding manufacturing systems. An accurate cycle-time estimate is an essential element of the cost estimate. This methodology, formulated by Munusamy and Clark,[4] is discussed in detail to provide information for readers who are using or anticipating the use of automated or robotic manufacturing systems.

TYPES OF WELDING MANUFACTURING SYSTEMS

A weld manufacturing system is comprised of one or more welding work centers. The entities at work in each welding work center are the operators, the welding machines, and the workpiece manipulators, positioners, and fixtures. For example, a welding work center may have one operator loading parts, four welding machines performing spot welds, another operator unloading parts, and a manipulator positioning parts for the welding machines. The times required for these entities to complete their corresponding tasks determine the cycle time for the system. Cycle time is the time required for the operators, welding machines, workpiece manipulators, positioners, and fixtures to complete their corresponding tasks.

Cycle time is the prominent factor that affects welding costs. However, estimating the cycle time can prove to be a difficult task in complex welding manufacturing systems that involve operator, machine, and manipulator interaction. This situation demands a general methodology for determining the cycle time to produce a weldment in various manufacturing systems.[5]

4. Munusamy, A., and G. Clark, 1997, *Formulating Weldment Cycle Time Problems,* Technical Report, Columbus, Ohio: The Ohio State University, Department of Industrial, Welding, and Systems Engineering.
5. See Reference 4.

Table 12.18
Equations Used to Estimate the Direct Costs of Arc Welding

Cost	Equation	
Gas cost per unit weight of deposited metal, \$/lb (\$/kg)	$\text{Cost}_{\text{Gas}} = \dfrac{G \times F}{D}$	(1)
Power cost per unit weight of deposited metal, \$/lb (\$/kg)	$\text{Cost}_{\text{Power}} = \dfrac{P \times V \times A}{1000 \times D}$	(2)
Cost of materials per unit weight of deposited metal, \$/lb (\$/kg)	$\text{Cost}_{\text{Materials}} = \dfrac{M}{E}$	(3)
Labor rate per unit weight of deposited metal, \$/lb (\$/kg)	$\text{Cost}_{\text{Labor}} = \dfrac{L \times K}{D \times 100}$	(4)
Overhead cost per unit weight of deposited metal, \$/lb (\$/kg)	$\text{Cost}_{\text{Overhead}} = \dfrac{O}{D \times \left(\dfrac{K}{100}\right)}$	(5)
Total cost of weld per unit weight of deposited metal \$/lb (\$/kg)	$\text{Cost}_{\text{Weld per unit length of deposited metal}} =$ Sum of Eqs. (1) through (5)	(6)
Total cost of weld per unit length of joint, \$/ft (\$/m)	$\text{Cost}_{\text{Weld per unit length of joint}} = \text{Cost}_{\text{Weld per unit length of deposited metal}} \times S$	(7)
Total cost of weld, \$	$\text{Total Cost}_{\text{Weld}} = \text{Cost}_{\text{Weld per unit length of deposited metal}} \times W$, or $7 \times N$	(8)
Total welding time, T (h)	$T = \dfrac{W}{(D \times K)}$	(9)
Total weight of weld metal, W (lb [kg])	$W = S \times N \times C$	(10)
Welding time per unit length for a specific joint, T_{Joint}	$T_{\text{Joint}} = W + (D \times K)$	(11)
Total consumables required	Electrode or wire (lb [kg]) $= W + E$	(12)
	SAW flux (lb [kg]) $= \dfrac{1.5\,W}{E}$	(13)
	Gas (ft^3 [m^3]) $= \dfrac{(F \times T)}{E}$	(14)

Key:
- A = Amperes
- C = Specific gravity of metal, lb/in.^{3} (kg/m^3)
- D = Deposition rate, lb/h (kg/h)
- F = Flow rate, cubic feet per hour (ft^3/h) (cubic meters per hour [m^3/h])
- G = Unit cost of gas or flux by volume, \$/ft^3 (\$/mm^3)
- E = Deposition efficiency, %
- K = Operator factor, %
- L = Labor rate, dollars (or other currency) per hour (\$/h)
- M = Cost of materials, \$/lb (\$/kg)
- N = Length of specified weld, in. (mm)
- O = Overhead rate, \$/h
- P = Power cost (\$/kWh)
- W = Total weight of weld metal,* lb/ft (kg/m)
- S = Cross-sectional area of weld joint, in.2 (mm2)
- T = Total welding time, h
- V = Volts

* Steel weighs 0.283 lb/in.^{3} (7.8×10^{-6} kg/mm^3)

Table 12.19
Arc Welding Cost Definitions

Variable	Definition
Deposition rate, *D*	Rate of weld metal deposited, lb/h (kg/h) (from data for 1 hour of continuous welding without arc stoppage)
Deposition efficiency, *E*	Ratio of weld metal deposited to total weight of electrode used, %
Operator factor, *K*	Ratio of arc hours to clock hours for a welder, %
Labor rate, *L*	Welder wages, $/h
Overhead rate, *O*	Cost of other business expenses, $/h
Power cost, *P*	Electricity, $/kWh
Amperes, *A* Volts, *V*	Vary according to specific welding procedure as well as electrode type and diameter
Material cost, *M*	Electrodes, $/lb ($/kg); wire, lb (kg); flux, $/lb ($/kg); and gas, $/ft^3 ($/m^3)

Table 12.20
Manual Arc Welding Values for Steel*

Process	Deposition Efficiency (*E*)	Operator Factor (*K*) Average	Material Costs (*M*), $/lb† Average Estimated Range‡	
SMAW	65%	25%	0.59 to 0.91	
GTAW	90%	25%	1.30 to 3.25	
GMAW	95%	35%	0.65 to 1.30	
FCAW	85%	35%	0.78 to 2.60	
SAW	98%	50%	Wire	0.59 to 0.72
			Flux	0.46 to 0.85

*Users are advised to use in-house time studies for actual values.
† Users are advised to evaluate the average estimated range of material costs to ensure they reflect current local prices ranges. If currency and units of weight are different from $/lb, the appropriate conversions must be made.
‡ Use current prices.

One such methodology that has been developed groups the various weldment manufacturing systems (centers) into three main categories: (1) a single sequential welding center, (2) a single simultaneous welding center, and (3) multiple welding centers. This methodology requires the creation of operator-machine charts to record the specific time inputs required by each of the entities (operators, welding machines, and manipulators) to perform tasks during a cycle time in which a weldment is produced by the center. Equations that yield the total cycle time can then be computed from an analysis of the operator-machine charts.

This methodology makes the following two important assumptions with respect to determining the cycle time of the various weldment manufacturing systems:

1. Activity times do not vary from weldment to weldment, that is, the activity times are constants that do not vary; and
2. Equipment operates without failure or disruption.

These assumptions result in cycle times that are optimistic and ignore any potential benefits from using buffers between welding machines or welding centers. That is, the average cycle times calculated by this methodology may be much shorter than they would be if allowances were made for variations in activity times and machine downtime due to equipment failures. However, buffers are incorporated to mitigate the effects of welding machine downtimes.

The following section describes the various categories of welding manufacturing systems as well as these concepts. Equations are then presented for use in calculating the cycle times for each of the manufacturing systems examined.

In complex automated and robotic production systems, welding centers may have one or more arc or resistance spot welding machines tended by one or more operators. In addition, weldments may be produced using multiple welding centers in which operators may tend multiple welding centers.

Once the cycle time has been estimated, the cost per weldment can be determined by the following:

1. Estimating the total number of weldments fabricated per hour or per shift, or during some other designated time period; and
2. Estimating the total cost by adding the costs of direct labor, direct materials, consumables, machines, overhead, and general and administrative activities.

To simplify cycle-time estimation, this methodology examines operator, machine, and manipulator functions as well as the time required to perform each entity's activities. The activity times include (1) setup time on the part of the operator, (2) load and unload times on the part of the operators, (3) welding times on the part of the machines, and (4) manipulation times on the part of the manipulators.

Setup time is the time required to prepare for the welding of several parts. Setup activities typically include securing the appropriate fixtures and setting process parameters. After completing setup activities, the system performs repetitive cycles. Each cycle results in the production of one or more weldments. The time required to place components of the weldment in the fixture or positioner and remove them after welding is referred to as the *load and unload time*. Manipulation time is defined as the time spent by the positioners or fixtures for manipulating workpieces. The manipulation time is zero if the positioners or fixtures do not move the workpieces, but only hold them.

Manipulators are complex machines that often cost as much or more than the welding machines they work in conjunction with. These positioners or fixtures are used to position, hold, or rotate the workpieces to be welded. They are programmed to manipulate the workpieces in a linear or angular motion and can rotate at any required angle. A circular manipulator moves the workpieces in an angular motion. In automated welding systems, manipulators are integrated with welding machines and controlled by the overall system controller.

Welding Center Configurations. The three weld manufacturing system configurations and their functions are categorized and defined as follows:

1. Single sequential welding center—One welding center that performs welding and loading or unloading sequentially but does not permit welding to occur while loading or unloading occurs;
2. Single simultaneous welding center—One welding center that performs the welding of one or more workpieces while one or more workpieces are being loaded and unloaded; and
3. Multiple welding centers—Several welding centers that perform welding and loading or unloading both simultaneously and sequentially. In this category, the workpieces flow from one welding center to another. This flow may be manual or mechanized. The centers may have multiple operators, or a single operator may tend multiple centers. For purposes of simplicity, this discussion excludes from consideration the case in which a single operator tends multiple centers in which workpieces do not flow from center to center.

As a welding center may have multiple operators and multiple welding machines, a wide range of weldment production variations are possible. The following system variations within each possible welding center configuration are examined in this section:

1. Single operator, single machine;
2. Single operator, multiple machines;
3. Multiple operators, single machine; and
4. Multiple operators, multiple machines.

FORMULAS

The production operation consists of repetitive activities. Considering that cycle time is the time required for the operators, welding machines, workpiece manipulators, positioners, and fixtures to complete their corresponding tasks, the welding center may produce more than one weld by the end of a cycle. For example, if a welding center produces one weld every minute, the weld has a cycle time of one minute. If a welding center produces two parts in a cycle one minute in duration, the cycle time is one minute. The cycle time is no shorter than the time the weld spends on a welding machine or than the total operator time spent for loading and unloading.

The following examples illustrate the method of estimating the cycle time for each type of welding center. Each example includes a schematic representation of the welding center.

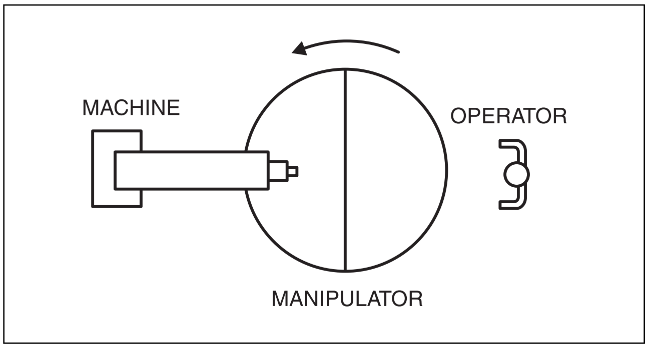


Figure 12.7—Simultaneous Welding Center with Single Operator, Single Machine

Simultaneous Welding Centers

Presented below are examples for the single operator, single machine and multiple operator, multiple machine simultaneous welding centers. In these examples, *CT* denotes cycle time, and *PC* denotes production quantity per cycle.

Single Operator, Single Machine System. Figure 12.7 depicts a typical simultaneous welding center in which a single operator and a single machine work at the same time. In this case, the loading and unloading activities may not take as long as the welding activity or they may take longer. Whichever activity is completed first must wait until the other activity has been completed.

In the operator-machine chart, shown in Figure 12.8, the time delay after completing both welding and unloading and loading before starting another cycle is referred to as the *manipulation time*. This is the time required for the circular manipulator to rotate the part for 180° (in this example). The cycle time is the time required for the operators, welding machines, workpiece manipulators, positioners, and fixtures to complete their corresponding tasks.

In the example, the simultaneous welding center with one operator and one machine produces one weldment per cycle. However, the welding center could produce multiple weldments per cycle with one operator and one welding machine. For instance, an operator could load two workpieces, after which the manipulator rotates 180°. While loading occurs, a single welding machine could move from the first workpiece to the second and weld the two workpieces.

In this case, the welding center is completing one weldment per cycle. The cycle time is calculated as follows:

$$CT = \text{Max}\,(L,\ W) + M \tag{12.7}$$

where

CT = Cycle time, seconds (s);
L = Average unloading and loading time, s; and
W = Average welding time, s; and
M = Manipulation time, s.

Multiple Operator, Multiple Machine System. Figure 12.9 depicts a typical simultaneous welding center comprised of two-machine system in which two operators and the two machines work at the same time. In this case, the workpiece may flow from one machine to another.

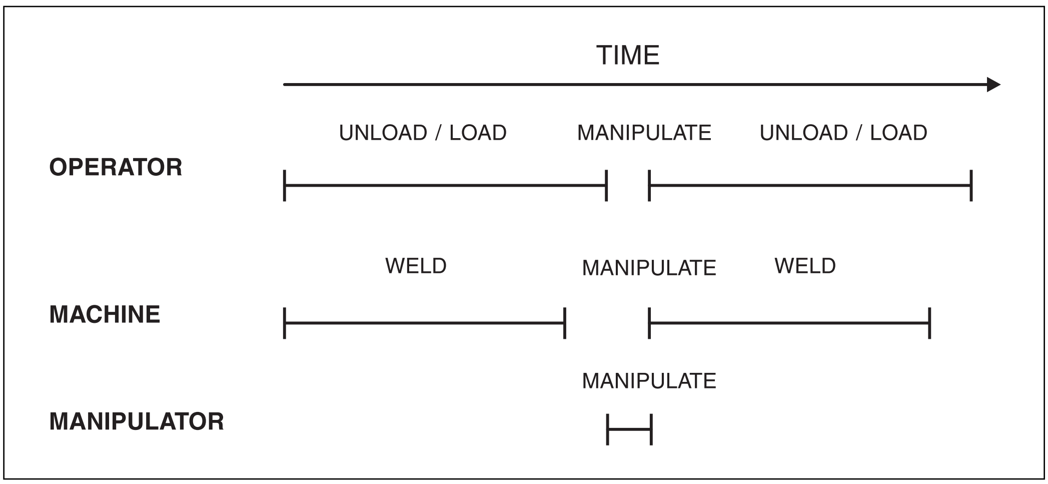


Figure 12.8 Operator-Machine Chart for a Single-Machine and Single-Operator Center

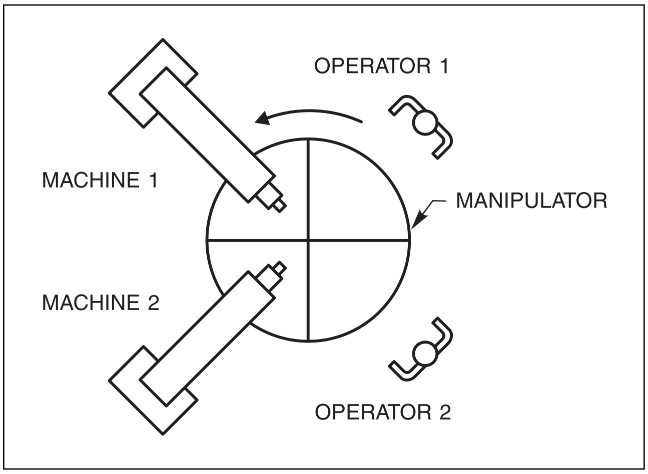


Figure 12.9—Simultaneous Welding Center with Multiple Operators and Multiple Machines

The following variables are used here to calculate cycle time for the two-operator, two-machine machine system:

L_1 = Average unloading and loading time for Operator 1, s;
L_2 = Average unloading and loading time for Operator 2, s;
W_1 = Average welding time for Machine 1; s and
W_2 = Average welding time for Machine 2, s.

The output of a center with multiple operators and multiple machines can further be divided into the following two subclasses, depending on workpiece flow: (1) workpieces flowing from machine to machine and (2) individual parts workpieces welded on a single machine. The primary difference between these two subclasses is the number of weldments produced per cycle.

In the case of workpiece flow from machine to machine, two operators and two machines work at the same time. Operator 1 mostly loads, and Operator 2 unloads the workpieces. The workpiece flows from one machine to another to complete the welding operation. In this example, the manipulator rotates 90° each cycle. Depending on the type and complexity of the product, the manipulator can rotate at any angle. This particular center produces one weldment per cycle.

The following equation is used to estimate cycle time for the multiple operator, multiple machine system in which the workpieces flow from machine to machine:

$$CT = \text{Max}\,(L_1,\ L_2,\ W_1,\ W_2) + M \qquad (12.8)$$

where

CT = Cycle time, s;
L_1 = Average unloading and loading time for Operator 1, s;
L_2 = Average unloading and loading time for Operator 2, s;
W_1 = Average welding time for Machine 1, s;
W_2 = Average welding time for Machine 2, s; and
M = Average manipulation time, s.

In the subclass in which individual workpieces are welded on a single machine, two operators and two machines work at the same time. The workpieces do not flow from machine to machine but are welded individually on each of the machines. The manipulator rotates 180° for each cycle. Operators 1 and 2 load and unload the workpieces while the two machines weld individually. This welding center produces two weldments per cycle.

The cycle time for the multiple operator, multiple machine system in which the workpieces are welded individually on each of the machines can be estimated with the following equation:

$$CT = \text{Max}\,(L_1,\ L_2,\ W_1,\ W_2) + M \qquad (12.9)$$

where

CT = Cycle time, s;
L_1 = Average loading and unloading time for Operator 1, s;
L_2 = Average loading and unloading time for Operator 2, s;
W_1 = Average welding time for Machine 1, s;
W_2 = Average welding time for Machine 2, s; and
M = Average manipulation time, s.

It should be noted that the cycle time estimates for these two subclasses are identical even though the number of weldments produced per cycle varies.

General Formulas for Simultaneous Welding Centers

Simplified equations that are used to estimate cycle time for a simultaneous weld manufacturing center comprised of two or more operators or welding machines are presented below. These expressions are not affected by the number of weldments produced per cycle.

Single Operator, Multiple Machine System. The following equation is used to estimate cycle time is for a simultaneous welding center with a single operator tending multiple welding machines:

$$CT = \text{Max}\left(L,\ W_1,\ W_2,\ldots\ W_m\right) + M \tag{12.10}$$

where

CT = Cycle time, s;
L = Average loading and unloading time, s;
W_1 = Average welding time for Machine 1, s;
W_2 = Average welding time for Machine 2, s;
W_m = Average welding time for welding machine m, s;
m = Total number of welding machines; and
M = Average manipulation time, s.

Multiple Operator, Single Machine System. The following equation is utilized to estimate cycle time for a welding center with multiple operators tending a single welding machine:

$$CT = \text{Max}\left(L_1,\ L_2,\ldots\ L_n, W\right) + M \tag{12.11}$$

where

CT = Cycle time, s;
L_1 = Average loading and unloading time for Operator 1, s;
L_2 = Average loading and unloading time for Operator 2, s;
L_n = Average loading and unloading time for operator n, s;
n = Total number of operators;
W = Average welding time for the welding machine, s; and
M = Average manipulation time, s.

Multiple Operator, Multiple Machine System. The following expression is used to estimate the cycle time for a welding center in which multiple operators tend multiple machines:

$$CT = \text{Max}\ (L_1,\ L_2,\ldots.\ L_n,\ W_1,\ W_2,\ldots\ W_m\ ) + M \tag{12.12}$$

where

CT = Cycle time, s;
L_1 = Average loading and unloading time for Operator 1, s;
L_2 = Average loading and unloading time for Operator 2, s;
L_n = Average loading and unloading time for operator n, s;
n = Total number of operators;
W_1 = Average welding time for Machine 1, s;
W_2 = Average welding time for Machine 2, s;
W_m = Average welding time for welding machine m, s;
m = Total number of welding machines; and
M = Average manipulation time, s.

A weld manufacturing center with three operators and four welding machines illustrates the application of Equation (12.12). Two operators place workpieces in two fixtures to load two machines, and the other operator unloads the weldments. While loading and unloading occur, the four welding machines complete all welds on the two workpieces that were loaded on the previous cycle. Thus, this welding center produces two weldments per cycle.

Consider the case in which the following times (in seconds) were expended by each of the following:

L_1 = Average loading and unloading time for Operator 1 = 20 s;
L_2 = Average loading and unloading time for Operator 2 = 20 s;
L_3 = Average loading and unloading time for Operator 3 = 25 s;
W_1 = Average welding time for Machine 1 = 27 s;
W_2 = Average welding time for Machine 2 = 27 s;
W_3 = Average welding time for Machine 3 = 31 s;
W_4 = Average welding time for Machine 4, = 31 s; and
M = Average manipulation time = 2 s.

The application of Equation (12.12) for this case results in the following:

$$CT = \text{Max}\ (20,\ 20,\ 25,\ 27,\ 27,\ 31,\ 31) + 2$$
$$= 33 \text{ seconds} \tag{12.13}$$

where CT denotes cycle time in seconds. Thus, Equation (12.12) provides an estimated cycle time of 33 seconds, and two weldments are fabricated per cycle.

A tandem or serial welding machine center with ten machines provides another example of the application of this method. One operator (e.g., Operator 1) loads a workpiece on each cycle. The workpiece travels down the tandem line on successive cycles, and ten welding machines complete all welds over a time period consisting of ten cycles. After ten cycles of welding, an operator (e.g., Operator 2) unloads the workpiece. The following times are assumed for this case:

Average loading and unloading time for Operator 1 (L_1), s = 40;
Average loading and unloading time for Operator 2 (L_2), s = 18;
Average welding time for Machine 1 (W_1), s = 28;
Average welding time for Machine 2 (W_2), s = 29;
Average welding time for Machine 3 (W_3), s = 7;

Average welding time for Machine 4 (W_4), s = 6;
Average welding time for Machine 5 (W_5), s = 25;
Average welding time for Machine 6 (W_6), s = 20;
Average welding time for Machine 7 (W_7), s = 21;
Average welding time for Machine 8 (W_8), s = 19;
Average welding time for Machine 9 (W_9), s = 12;
Average welding time for Machine 10 (W_{10}), s = 15; and
Average manipulation time (M), s = 3.

Thus, the cycle time for this weld manufacturing system can be estimated as follows:

$$CT = \text{Max}\,(40,\ 18,\ 28,\ 29,\ 7,\ 6,\ 25,\ 20,\ 21,\ 19,\ 12,\ 15) + 3 = 43 \text{ seconds}$$

$$PC = 1 \tag{12.14}$$

where

CT = Cycle time, s; and
PC = Production quantity per cycle.

Sequential Welding Centers

In a sequential welding center, either operator or the machine, but not both, are at work at any point of time during the cycle. For example, the operator would load or unload a workpiece or several workpieces on a manipulator while the welding machine is idle.

Figure 12.10 depicts a typical sequential welding center with a fixed welding manipulator (positioner) and two operators for loading or unloading the parts. After loading or unloading, the welding machine welds all workpieces in sequence until all required welding has been completed. Figure 12.11 presents the accompanying operator-machine chart for this sequence.

The cycle time for a sequential welding center with a fixed manipulator, one welding machine and two operators producing four weldments per cycle can be calculated using the following equation:

$$CT = \text{Max}\,(L_1,\ L_2) + W + 2M \tag{12.15}$$

where

L_1 = Average loading and unloading time for Operator 1, s;
L_2 = Average loading and unloading time for Operator 2, s;
W = Average welding time for the welding machine, s; and
M = Manipulation time, s.

The total manipulation time is $2M$ in this example since one manipulation occurs after unloading or loading and another occurs after welding. The Operator Chart in Figure 12.10 illustrates a welding center with a fixed manipulator. If the manipulator does not move the workpieces but only holds them, the manipulation time, M, is zero.

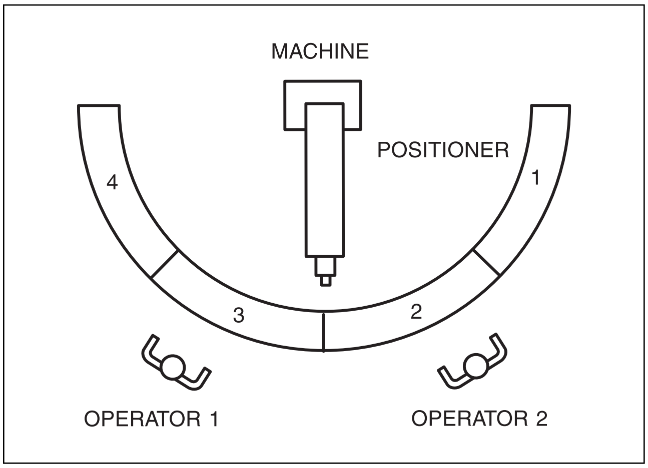


Figure 12.10—A Typical Sequential Welding Center with a Fixed Manipulator (Positioner) and Two Operators

General Formulas for Sequential Welding Centers

The general formulas for sequential welding centers are used to estimate the cycle time for all possible combinations of welding machines and operators. Following are equations that can be used to determine cycle time for sequential operations in various welding centers. The number of weldments produced in a cycle does not affect the calculation of the cycle time.

Single Operator, Single-Machine System. The following expression is used to calculate single-operator, single-machine cycle time for sequential operations.

$$CT = L + W + 2M \tag{12.16}$$

where

CT = Cycle time, s:
L = Average loading and unloading time, s;
W = Average welding time for the welding machine, s; and
M = Manipulation time, s.

Single-Operator, Multiple-Machine System. The following expression is used to calculate the cycle time

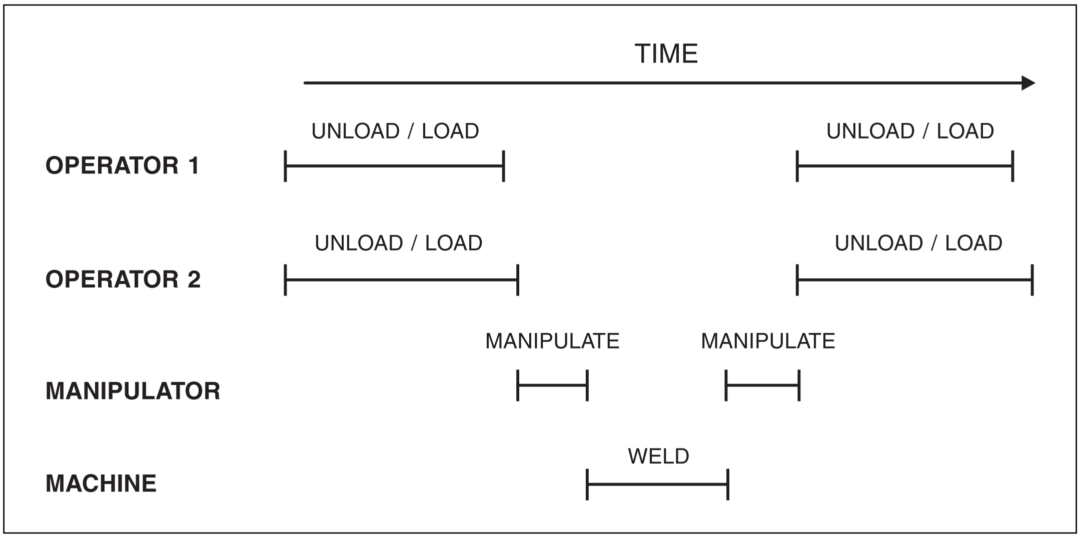


Figure 12.11—Operator-Machine Chart for a Sequential Welding Center with a Fixed Welding Manipulator and Two Operators

for a single-operator, multiple-machine welding center performing sequential operations:

$$CT = L + \mathrm{Max}\,(W_1, W_2, \ldots W_m) + 2M \tag{12.17}$$

where

CT = Cycle time, s;
L = Average loading and unloading time, s;
W_1 = Average welding time for Machine 1, s;
W_2 = Average welding time for Machine 2, s;
M = Total number of welding machines;
W_m = Average welding time for welding machine m, s;
m = Total number of welding machines; and
M = Average manipulation time, s.

Multiple-Operator, Single-Machine System. The following expression is used to calculate cycle time for a multiple-operator, single-machine welding center performing sequential operations:

$$CT = W + \mathrm{Max}\,(L_1, L_2, \ldots L_n) + 2M \tag{12.18}$$

where

CT = Cycle time, s;
L_1 = Average loading and unloading time for Operator 1, s;
L_2 = Average loading and unloading time for Operator 2, s;
L_n = Average loading and unloading time for operator n, s;
n = Total number of operators;
W = Average welding time for the welding machine, s; and
M = Manipulation time, s.

Multiple Operator, Multiple Machine System. The following expression is used to calculate cycle time for a multiple-operator, multiple-machine welding center performing sequential operations:

$$CT = \mathrm{Max}\left(L_1, L_2, \ldots L_n\right) + \mathrm{Max}\left(W_1, W_2, \ldots W_m\right) + 2M \tag{12.19}$$

where

CT = Cycle time, s;
L_1 = Average loading and unloading time for Operator 1, s;
L_2 = Average loading and unloading time for Operator 2, s;
L_n = Average loading and unloading time for operator n, s;
n = Total number of operators;
W_1 = Welding time for Machine 1, s;
W_2 = Welding time for Machine 2, s;
W_m = Welding time for welding machine m, s;
m = Total number of welding machines; and
M = Average manipulation time, s.

To illustrate the application of Equation 12.19, consider a three-machine welding center in which one operator (e.g., Operator 1) loads and another (e.g., Operator 2) unloads one workpiece per cycle. Once loaded, the workpiece travels to the three welding machines, where all welds are completed in three successive cycles. The three welding machines all work simultaneously, but loading and unloading cannot occur during the welding portion of the cycle. Thus the three welding machines complete all welding on the cycle after the workpiece is loaded. The times for this example are listed below:

L_1 = Loading and unloading for Operator 1 = 18 s;
L_2 = Loading and unloading for Operator 2, = 8 s;
W_1 = Average welding time for Machine 1 = 19 s;
W_2 = Average welding time for Machine 2 = 16 s;
W_3 = Average welding time for Machine 3 = 14 s; and
M = Average manipulation time, s = 3.

Thus, the estimated cycle time can be calculated as follows:

$$CT = \text{Max}\,(18,\ 8) + \text{Max}\,(19,\ 16,\ 14) + 2 \times 3 = 43 \text{ seconds} \tag{12.20}$$

where CT denotes cycle time in seconds.

Multiple Welding Centers

Multiple welding centers can be a combination of both simultaneous welding and sequential welding centers. One operator may handle more than one welding center. Workpieces flow between welding centers, and handling may be either manual or mechanized. This category can be divided into two subcategories, depending on whether each center has its own operator or whether a single operator tends multiple welding centers.

Multiple-Operator, Multiple-Welding Center System. In the case of multiple-operator, multiple-machine welding centers, each operator is assumed to work at an individual welding center. Since workpieces flow from one welding center to another, the system is a serial or tandem production line of weld centers, as illustrated in Figure 12.12. Workpiece flow between weld centers may be accomplished manually or by mechanization. It is also assumed that the capacity of the material handling system is greater than that of the welding centers. Thus, the material handling time can be ignored in calculating the cycle time for the system; the slowest welding center dictates the system capacity and cycle time.

The cycle time for a center with multiple operators with multiple welding centers can be calculated as follows:

$$CT = \text{Max}\,(CT_1,\ CT_2, \ldots\ CT_k) \tag{12.21}$$

where

CT = Cycle time, s;
CT_1 = Cycle time for Center 1, s;
CT_2 = Cycle time for Center 2, s;
CT_k = Cycle time for welding center k, s; and
k = Total number of welding centers.

The above equation assumes that each welding center produces the same number of weldments during a given cycle. The welding centers can be either simultaneous or sequential; in either case, the cycle times can be computed with the appropriate equation.

Single-Operator, Multiple-Welding-Center System. The general equation for the case of a single-operator, multiple-welding-center system involves the identification of the largest weld center with a single operator and the weld center cycle times. Figure 12.13

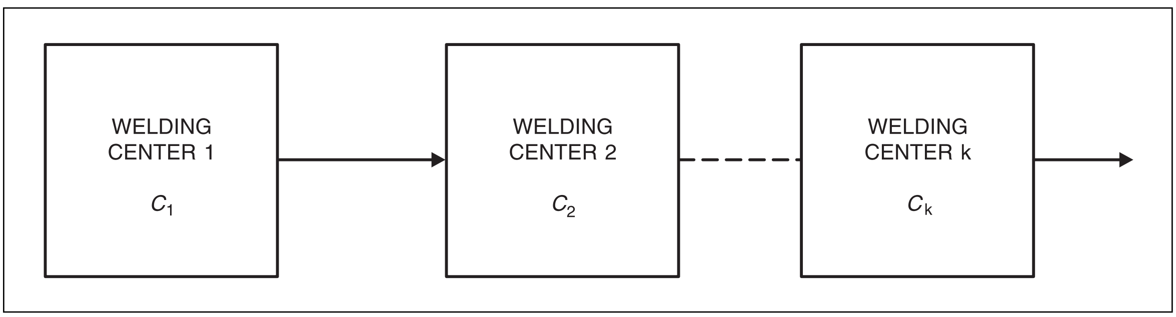


Figure 12.12—Multiple Operators with Multiple Centers

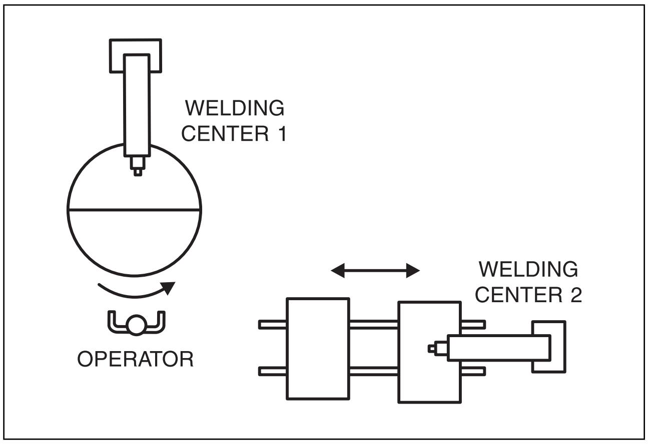


Figure 12.13—Single Operator, Two Welding Centers

illustrates a typical two-welding-center system incorporating one simultaneous welding center, Center 1, and one sequential welding center, Center 2. Workpieces flow from Center 1 to Center 2, as illustrated in Figure 12.13, although the direction of flow does not affect the calculation of the estimated cycle time.

The notations defined in Equation (12.21) are used to analyze this system, where CT_1 represents the cycle time for Center 1. The values of CT_1 and CT_2 are calculated, assuming the operator can allocate all of his or her time to each center. In this case, CT_1 is determined using the Equation (12.7) for a single simultaneous center, while CT_2 is determined from Equation (12.16) for a sequential center.

Also, it is assumed that O_1 denotes the total operator time consumed loading and unloading for Center 1, and O_2 is the total operator time consumed loading and unloading for Center 2. The term O_1 is the value of L in Equation (12.7), whereas O_2 is the value of L in Equation (12.16).

To identify the time constraints, all the activities performed in a welding center must be coordinated to avoid waiting time between activities, which would constitute a time constraint. The operator-machine chart presented in Figure 12.14 depicts a case in which the operator becomes the cycle time constraint. That is, $O_1 + O_2 > CT_1$ and $O_1 + O_2 > CT_2$. In this case, the single operator requires more time than the cycle time required for a system with two operators. It should be noted that the cycle time is $O_1 + O_2$.

In the following example, the operator-machine chart presented in Figure 12.15 depicts the case in which Weld Center 1 is the cycle-time constraint, that is, $CT_1 > O_1 + O_2$ and $CT_1 > CT_2$, where CT_1 represents the cycle time in seconds; O_1 represents the total operator time consumed at Center 1 in seconds; O_2 represents the total operator time consumed at Center 2 in seconds, and CT_2 represents the cycle time for Welding Center 2 in seconds. In this case, if O_1 is greater than CT_1 and O_2, the time consumed by Operator 2 in seconds, the operator would be the cycle-time constraint.

The operator-machine chart presented in Figure 12.16 depicts the case in which Welding Center 2 is the

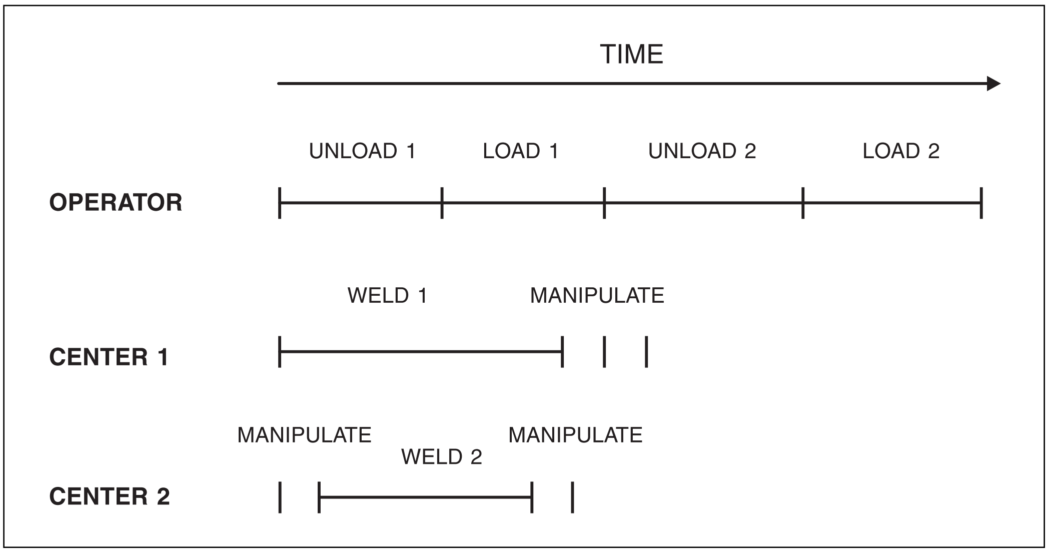


Figure 12.14—Operator-Machine Chart Indicating the Operator as the Time Constraint

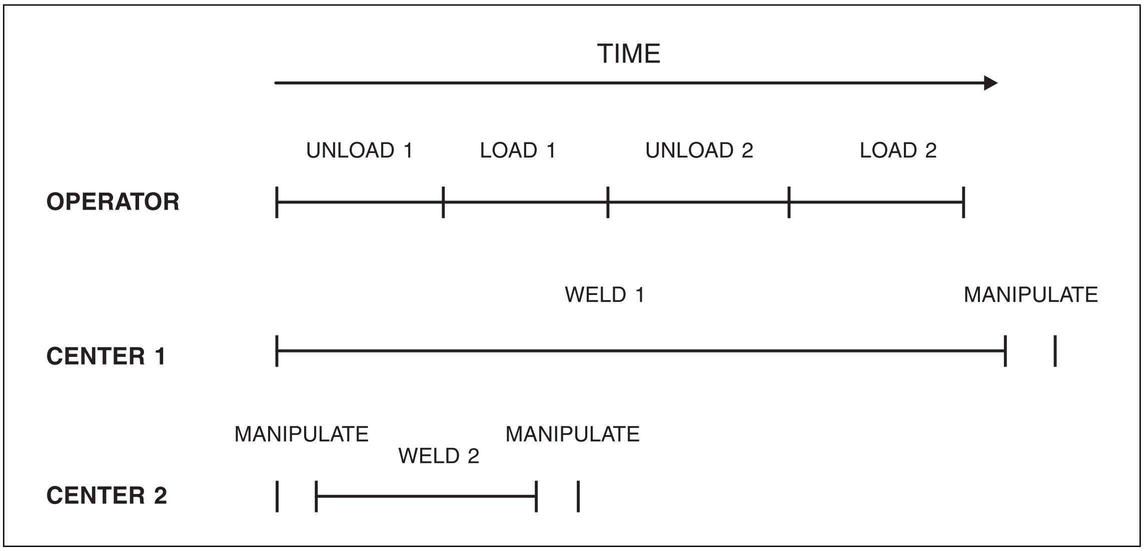


Figure 12.15—Operator-Machine Chart Indicating Welding Center 1 as the Cycle-Time Constraint

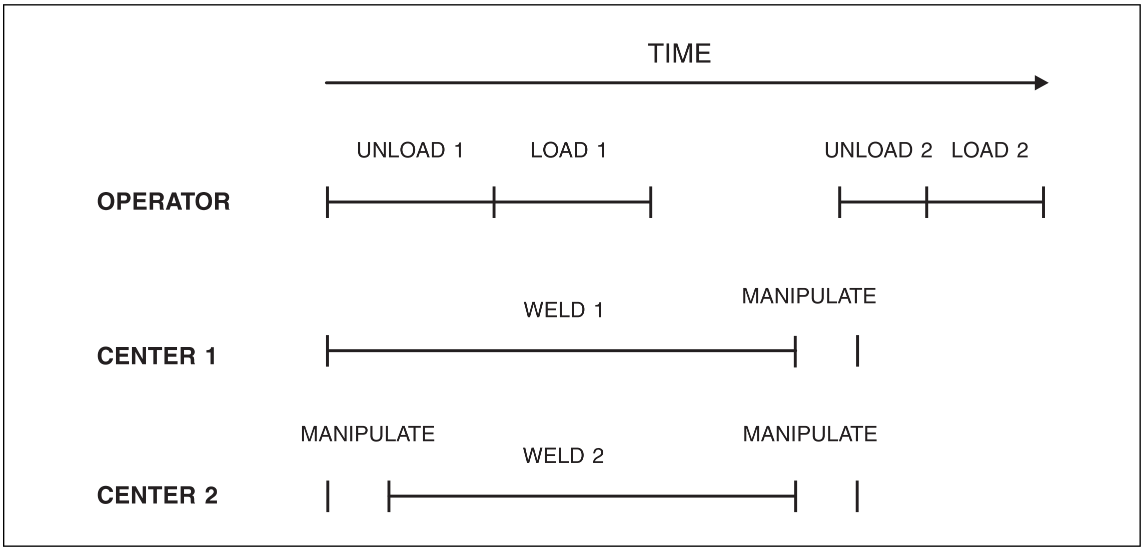


Figure 12.16—Operator-Machine Chart Indicating Welding Center 2 as the Cycle-Time Constraint

cycle time constraint, that is, $CT_2 > O_1 + O_2$ and $C_1 < C_2$, where CT_2 represented the cycle time of Machine 2 in seconds; O_1 represents the total operator time consumed at Center 1 in seconds; and O_2 represents the total operator time consumed at Center 2 in seconds.

The following equation is employed to estimate the cycle time for a weld manufacturing center consisting of one operator and two welding centers:

$$CT = \text{Max}\,(O_1 + O_2,\ CT_1,\ CT_2) \qquad (12.22)$$

where

CT = Cycle time, s;
O_1 = Total operator time consumed at Center 1, s;
O_2 = Total operator time consumed at Center 2, s;
CT_1 = Cycle time for Center 1; and
CT_2 = Cycle time for Center 2.

In general, for one operator tending k welding centers, the cycle time is the maximum of the total operator time compared to the individual center cycle times, assuming a dedicated operator. This expression is written as follows:

$$CT = \text{Max}\,(O_1 + O_2 + \ldots + O_k,\ CT_1,\ CT_2, \ldots,\ CT_k) \tag{12.23}$$

where

CT = Cycle time, s;
O_1 = Total operator time at Center 1, s;
O_2 = Total operator time at Center 2, s;
O_k = Total operator time at welding center k, s;
k = Total number of welding centers
CT_1 = Cycle time for Center 1, s;
CT_2 = Cycle time for Center 2, s; and
CT_k = Cycle time for welding center k, s.

ECONOMICS OF RESISTANCE SPOT WELDING

Many of the principles of cost estimating presented in previous sections for other welding processes hold true for resistance spot welding. Although some repetition is inevitable, this section specifically addresses calculating costs for resistance spot welding.

The five main factors involved in the manufacturing cost of a weldment using resistance spot welding machines are the following:

1. Set-up or line changeover costs,
2. Direct labor cost,
3. Direct material cost,
4. Cost of small tools and fixtures, and
5. Overhead or indirect costs.

COST MODEL

The costs of consumables such as electrodes are important considerations; however, the viewpoint assumed in this model is that these costs are included in overhead costs when estimating the total cost to produce a weldment. Methods for estimating the costs of consumables appear in a subsection below.

Overhead and indirect costs represent a major portion of weldment costs, and the method for allocating indirect costs affects price competitiveness and resource management decisions. Many companies assign unique overhead rates to various cost centers. For example, welding operations may have a different overhead rate than forming or stamping operations. This cost model assumes that the overhead rate for welding operations is the same for each welding machine or welding work center.

The cost model used in this section to estimate manufacturing costs exclusive of general and administrative expenses is as follows:[6]

$$TMC = \frac{SETC}{LOT} + \frac{CT}{PC \times 3600}\left[NO\left(L + LOVH\right) + \left(NWC \times WCOVH\right)\right] + DMC + ST \tag{12.24}$$

where

TMC = Total manufacturing costs of a weldment, \$;
$SETC$ = Total set-up or changeover costs, including overhead, \$;
LOT = Lot size or mean number of weldments produced per setup;
CT = Cycle time or mean time between production of weldments, s;
PC = Production quantities per cycle;
NO = Total number of operators;
L = Labor rate per person per hour, \$;
$LOVH$ = Labor overhead rate per hour, \$;
NWC = Total number of welding work centers;
$WOCVH$ = Welding work center overhead rate per work center per hour, \$;
DMC = Direct material cost per weldment, \$; and
ST = Cost of small tools and fixtures per weldment, \$.

The cost model stated in Equation (12.24) utilizes a method for allocating overhead that is compatible with the accounting methods for many companies to illustrate the computation of a cost estimate. Two overhead rates are defined—one for labor ($LOVH$) and one for work centers ($WCOVH$). A company that only uses one of these rates can assign a value of zero to the other.

To determine overhead rates, all indirect or fixed costs in a time period such as a year are assigned to one of two cost pools, i.e., a labor pool and a work center pool. Each pool has its own cost driver—direct labor hours for the direct labor pool and assignable work center hours for the work center pool. Work center hours are assignable when the work center is scheduled

6. Munusamy, A., G. Clark, and T. Miller, 1996, *Resistance Spot Welding Cost Model*, Working Paper, Columbus, Ohio: The Ohio State University, Department of Industrial, Welding, and Systems Engineering.

to produce a particular weldment. To calculate the overhead rates, the total costs in each pool are divided by the total of the pool's cost driver for the past year.

The use of only one overhead rate can significantly affect the cost estimate. For example, a manufacturer uses one overhead rate, *LOVH*, for direct labor hours. Two weldments, A and B, are produced in the welding manufacturing center. Three operators produce A, and one operator tends the welding work center producing B. Assuming that the cycle times (*CT*) and total production quantities per cycle (*PC*) are the same for Weldments A and B, Weldment A bears three times the indirect cost as compared to B because B requires three operators.

In another example, Weldments C and D are produced by spot welding work centers. In this case, only the work center overhead rate, *WCOVH*, is used. One operator tends the work center producing C, and another operator tends two work centers, producing D. If the cycle times and the production quantities produced per cycle are the same, Weldment D has twice the overhead cost of weldment C because D requires two work centers.

Estimating Spot Welding Machine Cycle Time

Several different cycle times are important when calculating spot welding product costs. They are defined as follows:

Spot welding system cycle time (*CT* in the above model)—Time interval between the production of one or more weldments by the spot welding system. Some spot welding systems produce two or more weldments in a given cycle ($PC \geq 2$);

Welding center cycle time—Time interval between the production of one or more weldments by a welding center. If the spot welding system has a single machine, the spot welding system's cycle time and the welding center's cycle times are identical;

Welding machine cycle time—Time required by a single welding machine to complete all spot welds assigned to that welding machine. This time includes the welding times and the times required to move welding heads or electrodes to their proper positions;

Machine cycle time—Time interval between the production of a set of spot welds by a welding machine. A welding machine may perform multiple machine cycles during its welding machine cycle. This occurs when a welding machine produces a group of spot welds and then proceeds to the production of another group; and

Spot weld cycle time—Time required to produce a group of spot welds once the welding machine has moved the electrodes to their proper positions. The spot weld cycle time includes the time to apply contact pressure, perform the welds, and apply heat treatment.

Each cycle time defined above has an associated cycle that consists of the activities performed during the cycle time. For example, a spot weld cycle consists of the activities accomplished during the spot cycle time. These are presented in Table 12.21.

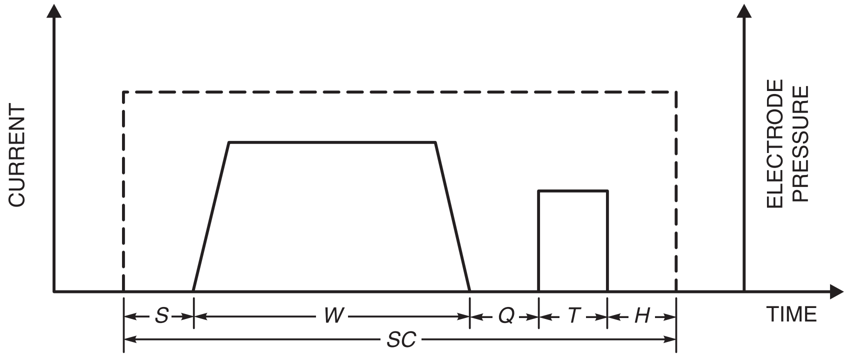
Total cycle time is important to the process of determining the costs of labor, equipment, energy, and consumables. Figure 12.17 depicts a typical resistance spot weld cycle showing squeeze time, weld time, quench time, temper time, hold time, and spot cycle time.

The spot welding cycle time is also important in determining the overall welding machine cycle time and air consumption costs. It may also affect coolant consumption costs. The weld and temper times are important in calculating energy costs.

A machine cycle includes a spot weld cycle *(WMC)*. However, it should be noted that a welding machine

Table 12.21
Symbols and Definitions for a Typical Spot Weld Cycle

Symbol	Operation	Definition
S	Squeeze time	The time for the electrodes to close and develop contact pressure on the workpiece.
W	Weld time	The total time current flows in order to form the weld nugget and accomplish joining. This time interval includes preheat and postheat times.
Q	Quench time	Cooling time in the interval between weld and tempering times.
T	Temper time	Time to heat treat after cooling.
H	Hold time	Time after tempering when the electrodes continue to maintain contact pressure.
SC	Spot weld cycle time	Total time the electrodes contact the workpiece.



Key:
= Current
= Electrode pressure
S = Squeeze time, s
W = Weld time, s
Q = Quench time, s
T = Temperature, s
H = Hold time, s
SC = Spot cycle time, s

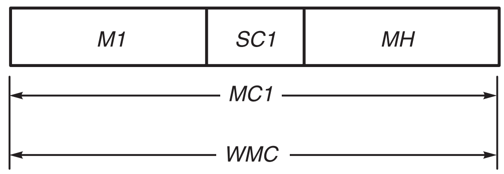
Figure 12.17—Typical Resistance Spot Welding Cycle

that has only a single machine cycle is not limited to one weld. It produces all the spot welds assigned to it in a single spot weld cycle *(SC1)*. Some resistance welding machines produce welds in two spot cycles. They move the electrodes to perform the first spot weld cycle *(SC1)* and then move the electrodes to produce the second spot weld cycle *(SC2)*.

Figure 12.18 depicts the activities for a welding machine with a single machine cycle showing. Figure 12.19 illustrates the activities performed with a welding machine that has two machine cycles.

The activity representation depicted in Figures 12.18 and 12.19 permits considerable flexibility with respect to the number of welding heads used by a welding machine. In Figure 12.19, the welding machine might use the same welding head to accomplish the two spot weld cycles, but the model can also represent multiple heads on a particular spot weld cycle as well as a particular spot weld cycle with its own unique set of heads. The only requirement is that a given spot weld cycle conform to the activity times shown in Figure 12.18.

When the welding machine uses the same welding head or heads to accomplish *SC1* and *SC2*, then *M2* represents the time to move those heads from the *SC1* position to the *SC2* position. When the welding machine uses different heads, *M2* represents the movement of heads involved in *SC1* back to a home position and the movement of heads for *SC2* to its position.



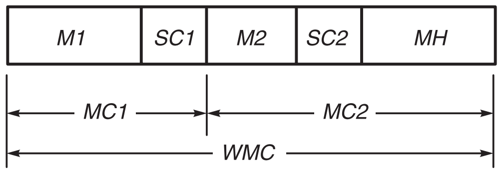
Key:
M1 = Movement of electrodes from home position to the position required for the first weld cycle
SC1 = First spot weld cycle
MH = Movement of electrodes back to home position from the last spot weld cycle position
MC1 = First machine cycle
WMC = Spot weld cycle

Figure 12.18—Spot Welding Machine Activities During a Single Machine Cycle

Resistance Welding Machine Consumable Costs

The cost models for each of the consumable costs for a resistance welding machine are represented in the equations below and include the following factors:

1. Replacement of electrodes,



Key:
$M1$ = Movement of electrodes from home position to the position required for the first weld cycle
$SC1$ = First spot weld cycle
$M2$ = Movement of electrodes away from the first spot weld cycle position and the placement of the electrodes at the second spot weld cycle position
$SC2$ = Second spot weld cycle
MH = Movement of electrodes back to home position from the last spot weld cycle position
$MC1$ = First machine cycle
$MC2$ = Second machine cycle
WMC = Spot weld cycle

Figure 12.19—Spot Welding Machine Activities During Two Machine Cycles

2. Tool wear costs,
3. Cooling water,
4. Air,
5. Pneumatic system,
6. Power, and
7. Total spot weld time.

Electrode Replacement. The following equation can be used to calculate the cost of electrode replacement per weldment:

$$EC = \frac{ae}{bc}\left(q + \frac{Lt}{60}\right) \tag{12.25}$$

where

EC = Cost of electrode replacement per weldment, \$;
a = Number of spot welds made per weldment;
e = Length of electrode material removed in a single dressing operation, in. (mm);
b = Allowable electrode length to be dressed in one electrode, in. (mm);
c = Average number of welds made between two successive dressing operations,
q = Cost of one electrode, \$;
L = Labor rate per person per hour, \$; and
t = Average time to replace one electrode, minutes.

Tool Wear Cost. The following equation can be used to calculate the tool wear cost *(TWC)* per unit:

$$TWC = \frac{ya}{cx} \tag{12.26}$$

where

TWC = Tool wear cost per weldment, \$;
y = Cost of a single dressing tool, \$;
a = Number of spot welds made per weldment;
c = Average number of welds made between two successive dressing operations, and
x = Average number of dressing operations per tool.

Cooling Water. The following equation can be used to calculate water costs (WC), including cooling:

$$WC = WR \times TST \tag{12.27}$$

where

WC = Cost of water, \$/gal (\$/L);
WR = Water consumption rate, cubic foot per minute (ft^3/min) (cubic meter per minute [m^3/min]); and
TST = Total spot weld time, min.

Air. The following equation can be used to calculate air costs (AC) for pneumatic systems:

$$AC = AR \times AC \times TST \tag{12.28}$$

where

AC = Cost of air, \$/ft^3/min (\$/m^3/min);
ACR = Air consumption rate, ft^3/min (m^3/min);
AR = Air cost rate, \$/ft^3 (\$/m^3); and
TST = Total spot weld time, min.

Power. The following equation can be used to calculate the cost of power *(PCS)*:

$$PCS = \frac{PR \times V \times A \times TWT}{1000 \times 60} \tag{12.29}$$

where

PCS = Power cost; \$/kWh;
PR = Power rate; \$/kWh;
V = Voltage;
A = Amperage; and
TWT = Total weld and temper times for all spot welds, min.(see Figure 12.17).

Total Spot Weld Time. The following equation can be used to calculate the total spot weld time (TST):

$$TST = ACT \times NS \tag{12.30}$$

where

TST = Total spot weld time, min;
ACT = Average spot weld cycle time, s (average value of SC in Figure 12.19); and
NS = Total number of spot welds.

CAPITAL INVESTMENT IN WELDING AUTOMATION AND ROBOTICS

Capital investments in automated and robotic equipment can result in reduced costs and an improved manufacturing operation. The investments can be simple and low in cost, such as those incurred in replacing shielded metal arc welding with a continuous wire welding process such as gas metal arc or flux cored arc welding. On the other hand, these investments can be complex and costly, such as those incurred in converting to a computer-controlled, robotic, flexible manufacturing cell that replaces several operations.

JUSTIFICATION OF CAPITAL EQUIPMENT

Before committing investment capital, a financial analysis should be conducted in which the costs and potential benefits of the investment are forecast. This cost/benefit analysis should verify that the proposed equipment or facility is economically viable. The cost forecast should include the following:

1. Engineering, purchase, and installation costs of the proposed production equipment;
2. Cost of any peripheral equipment required to operate the proposed equipment;
3. Annual operating costs of the production and support equipment;
4. Maintenance cost of the production and support equipment; and
5. Personnel training.

The potential benefits of performing a cost/benefit analysis with respect to capital investment include the following:

1. Cost savings on discontinued operations;
2. Savings resulting from improved quality;
3. Profit from increased production;
4. Identifiable savings from safety improvements; and
5. Reduction in work-in-process inventory.

A discounted cash flow analysis should also be prepared to provide the annual and cumulative financial results of the capital investment. To prepare a discounted cash flow analysis, the estimator must consider the time periods when the costs are incurred and when the benefits are expected to be achieved. The analysis should reflect current or projected interest rates and a calculation of the time required for recovery of capital expenditures.

Several factors should be considered in order to determine the most effective capital investments and to elaborate the cost analysis. These factors are discussed below.

Production Volume Estimates

The first priority in planning for welding shop improvements is a firmly established production volume forecast. A production volume of a specified minimum number of units is required. Generally, the cost of manufacturing equipment is proportional to its production capacity. For long production runs, dedicated automation is frequently more efficient. A pipe mill is a pertinent example of the manner in which dedicated automation results in low product (in this case, transmission pipe) manufacturing costs. However, these mills are high-capital facilities that are dedicated to the manufacture of one specific product only (i.e., pipe).

For relatively short production runs, flexible, multipurpose automation can be used to an advantage even though it may be expensive. An example of flexible automation is a microprocessor-controlled robot. In other cases, investment in semiautomatic welding equipment and additional fixtures may result in significant cost benefits.

Thus, the type of product and the production quantities should be forecast to determine whether dedicated or flexible automatic or semiautomatic equipment should be purchased. The relative unit cost of manual and semiautomatic manufacturing, dedicated automation, and flexible manufacturing is a function of volume. The relationship is different for every manufacturing plant, but the relative productivity of these three approaches to manufacturing is illustrated in Figure 12.20.

When automated or robotic systems are contemplated, special consideration must be given to setting up subsystems to support the operations. Modifications may be needed in such areas as floor space, material

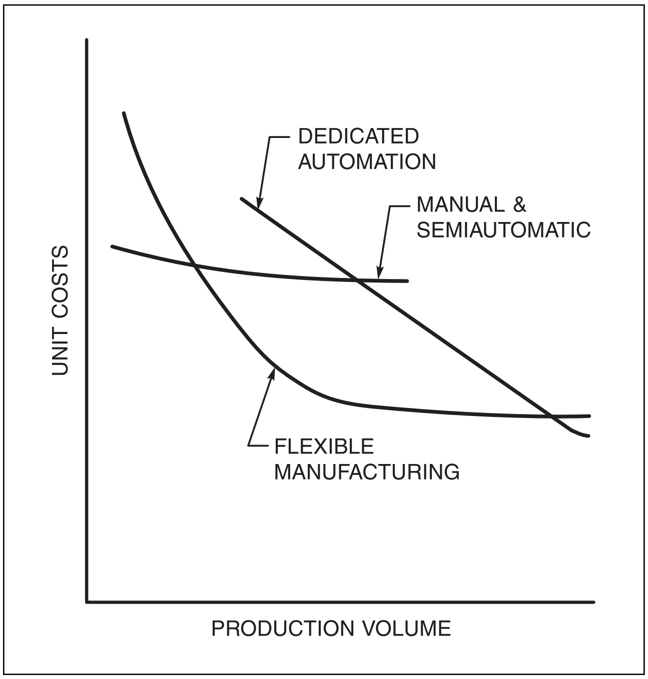


Figure 12.20—Effect of Production Volume on Unit Cost for Dedicated, Manual, and Flexible Manufacturing Stations

handling, and product design. A safety system appropriate to the automated equipment must be carefully planned and implemented.

Installation Costs. Several resource requirements are unique to automated equipment. Planning must include provisions for adequate floor space, foundations, special installation equipment, and utilities.[7] It is common for the cost of installing automated equipment to range from 5% to 10% of the initial cost of the machine. Therefore, it is important to plan for these costs and include them in the economic analyses.

Workpiece Geometry. Welding with special-purpose automated equipment may require geometric simplicity of the workpieces to accommodate straight or circular welds. For example, tubes and pipes can be welded relatively quickly and at low cost because of the simplicity of their geometry. Workpieces requiring complicated weld paths may have to be welded manually unless the plant can invest in special-purpose equipment. In this case, users should specify equipment that can be preprogrammed to track the weld path. Alternatively, equipment that has a seam tracking device or is designed with permanent mechanical motion paths using cams, gears, and templates can be used. The thickness and size of the workpiece as well as a requirement for mobility may favor special purpose equipment.

Workpiece Accuracy. Automated welding equipment generally requires more accurate preparation of components than would be needed for manual welding. A welder visually senses variations in parts and instinctively makes corrections to compensate for them. Sensory systems and adaptive feedback controls can be added to a welding machine to correct for joint location and width, but the equipment is expensive and primitive relative to the skilled response of a human welder. The better solution would be to improve the component accuracy and assembly fitup. The inherent accuracy of the welding machine is also an important factor. The accuracy of the components is meaningless if the tracking of the welding head and the welding current controls are not precisely coordinated to deposit the correct weld size in the correct location.

Material Handling. The continuous character of automated welding frequently requires the integration of associated material-handling systems to function in sequence with the welding machine. Manually loaded welding machines are paced by the operator. In many cases, the capacity for automatic loading and automatic ejection of parts is incorporated in the welding machine. Conveyors or large containers are used to transport workpieces to the machine and subsequently transfer them to the next manufacturing operation. Material handling equipment can improve the productivity of shops using manual and semiautomatic welding equipment.

Safety. Safety considerations require care in the set up, operation, and maintenance of automated welding equipment. Consequently, the implementation of safety measures involves expenditures. Most automatic welding machines not only have rapidly moving components but also fail to sense the presence of operating and maintenance personnel. Typical safety requirements for these machines include fail-safe systems with easy access to emergency stop buttons that halt operations immediately. During normal weld production, the operator and other personnel must remain outside the operating envelope of the machine. Mechanical guards that interlock with the machine to prevent inadvertent or careless operation of the machine during maintenance are used.[8]

7. Planning for automated equipment is discussed in Chapter 11 of this volume.

8. Additional information on safe practices is presented in Chapter 17 of this volume.

Advantages of Automated and Robotic Systems

A number of cost benefits can be derived from the implementation of automated and robotic welding systems. These include improved deposition efficiency, improved operator factor, and the overall improvement factor, all of which are discussed below.

Improved Deposition Efficiency. The use of automation yields significant improvements in deposition efficiency as compared to manual welding. One of the advantages of automation is the precision with which the equipment is able to repeat each activity. The welding current and travel speed can be programmed to yield the exact weld size required and minimize weld spatter. Automation thus improves the deposition efficiency.

Improved Operator Factor. Significant improvements in the operator factor can be achieved with automated welding equipment, as indicated in Figure 12.20. However, operator factor improvements depend on the requirements of the product and the production volume. When large weld deposits are required on a single weldment, a considerable amount of continuous welding is necessary. For example, the girth seam in a 15 ft (4.6 m) diameter pressure vessel with a two inch (50 mm) wall thickness may require eight hours of continuous work for an automatic submerged arc welding station. On the other hand, a robotic gas metal arc welding station may require only two or three minutes to weld a frame for a furniture manufacturer, in which case a steady flow of frames is required to take full advantage of the productive capacity of the robot.

Efficient Weld Joint Design. Another benefit of the utilization of automated welding equipment is the capability for higher filler metal deposition rates, which permits the use of more efficient weld joint designs. For example, with automation it might be possible to replace a 60° V-groove with a square-groove joint design. Such a change may permit the use of higher welding speeds and a reduction in the amount of deposited metal required. Decreased variation in weld size, another potential benefit, results in the consumption of less filler metal and minimizes overwelding. As explained in the section "Unforeseen Costs," overwelding is a negative factor in both labor and material costs.

Overall Improvement Factor. Several factors that may result in increased productivity with automated equipment have been considered above. The term *overall improvement factor* is used to refer to the product of these factors, namely, improved weld deposition efficiency, improved operator factor, and efficient weld design.

Typically, the substitution of an automated gas metal arc welding system for semiautomatic welding to produce fillet welds can result in a welding process improvement factor of approximately 1.4 for the welding process, a reduction in overwelding by a factor of approximately 2.25, and improvement in the operator factor by approximately 2.5. Overall, automatic gas metal arc welding may be nearly eight times more productive than semiautomatic gas metal arc welding and significantly more productive than a shielded metal arc welding station.

Combined Operations. The automation of welding equipment can allow the simultaneous operation of two or more welding heads. The simultaneously welding of both fillets of a double fillet weld is a common practice in applications such as shipbuilding and girder fabrication. Computer-controlled flexible manufacturing cells can extend the concept of combined operations to include nonwelding activities such as fitting, punching, or gouging. The cost savings can be leveraged significantly by integrating several operations within a cell.

MANUFACTURING OPTIONS

Several manufacturing options can be implemented to achieve high quality at a competitive cost. Among these are agile manufacturing and improved throughput, which are discussed in this section.

Agile Manufacturing

The need to supply products to customers at the required quality level, at a competitive cost, and in a timely manner has led to the implementation of agile manufacturing, which affects the way products are manufactured, thus impacting costs. The option referred to as *agile manufacturing* focuses attention on the core competencies a manufacturing enterprise must possess to be competitive. The goal of agile manufacturing is to reduce the output of the economic lot size to one part per batch.

With respect to welding, agile manufacturing considers cycle-time costs. As the term *cycle time* refers to the period of time that transpires between the moment a part is loaded and the time it is unloaded, the term *cycle-time cost* denotes the monetary value (in dollars or other currency) placed on the worker hours that are consumed in one cycle. The critical focus used in this approach is time compression—specifically, reducing the amount of time spent from the moment of a weld's conceptualization to the delivery of the product. To achieve this time compression, a manufacturer can employ techniques such as (1) strategic alliances between customers, suppliers, equipment vendors, and manufacturers and (2) concurrency of production functions. These techniques or a combination of these and other strategies result in the reduction of total cycle time to its lowest possible level.

Agile manufacturing minimizes all nonarc time spent by the welder or operator. As a result, the actual arc time, which is the only value-added time the welder or operator contributes, is maximized.

Improved Throughput

To reduce the total cycle time associated with product fabrication, manufacturers emphasize improved throughput, defined as the sum of the production capacity of a fabricating system and the time required to complete the product. Throughput can be improved by implementing agile manufacturing techniques.

An important concept of agile manufacturing is setting up modularized facilities—work stations that include equipment and tooling, that have been planned and designed for the maximum efficiency of the setup and welding or cutting cycle for a complete unit or product. Modularized facilities can be utilized to provide low unit cost of customized products.

An advantage of modular operations is that machines are not tied up with long production runs and are therefore available to fabricate other parts needed for the same job or other scheduled jobs. In addition, the amount of work in progress is reduced to an economic level, resulting in reduced overhead and operating costs. One of the most important advantages of modularized operations is the flexibility gained by the manufacturer with respect to responding to customer requests faster and at lower cost.

When considering a conversion to modularization, it is necessary to reexamine the more traditional concept of running parts in large economic order quantities to achieve the lowest unit cost. In the economic order quantity system, the costs incurred in setup, welding, and cutting are spread over the total number of parts in a production run. Achieving the lowest unit cost may require that the largest possible production run be made. However, this often leads to over-runs or proves to be inefficient in some other area. This approach can also result in storage problems and high inventory costs.

CONTROL OF WELDING COSTS

Some of the costs of welding variables can be managed to improve the overall cost. For example, for a given application, some processes are more economical than others. Correct joint design can decrease the required amount of filler metal. Economies can be achieved by careful preassembly and fitting. Automated welding can be implemented to produce lower per-piece cost. All of these factors can be planned for maximum efficiency. However, sometimes costs are "hidden" in operations that are not known or anticipated. This section discusses the manageable costs and addresses some of the unforeseen costs.

MANAGEABLE COSTS

Manageable costs include factors such as joint design, weldment design, mistake-proofing layouts and fitups, process selection, eliminating operations, production planning, welding procedures, supporting activities, and field welding. These are explained below.

Joint Design

As the fundamental factor in welding cost is the weight of deposited metal, all other welding costs can be related to this variable. Therefore, any change that results in a decrease of deposited metal will also reduce each welding cost item.

Deposited metal weights can be reduced in several ways. The simplest is to reduce the cross-sectional area of the joint by decreasing the root opening, using a root face on groove welds, decreasing the groove angle, or using double V- or U-grooves, as shown in Figure 12.21.

To achieve a reduction in cross section, the parts must be cut and fit accurately so that the overall dimensions meet the requirements of the assembly. If the groove angle is too small or the root face is too wide, the possibility of incomplete joint penetration or other unacceptable weld discontinuities may be increased. Defective welds are very costly because they must be removed and the joint must be rewelded. Changes in groove geometry should be carefully analyzed and tested before being implemented to assure that overall dimensions meet the specification requirements and that weld quality will be acceptable. Additional information on cost savings related to joint design is presented in Chapter 5 of this volume.

Weldment Design

A source of cost reduction lies in the redesign of weldments to take full advantage of the accuracy of computer-controlled thermal machining centers and their ability to produce complex geometry inexpensively. Improved design eliminates the need for layout, improves quality, and makes operations mistake-proof. Weld quality improves when the quality of

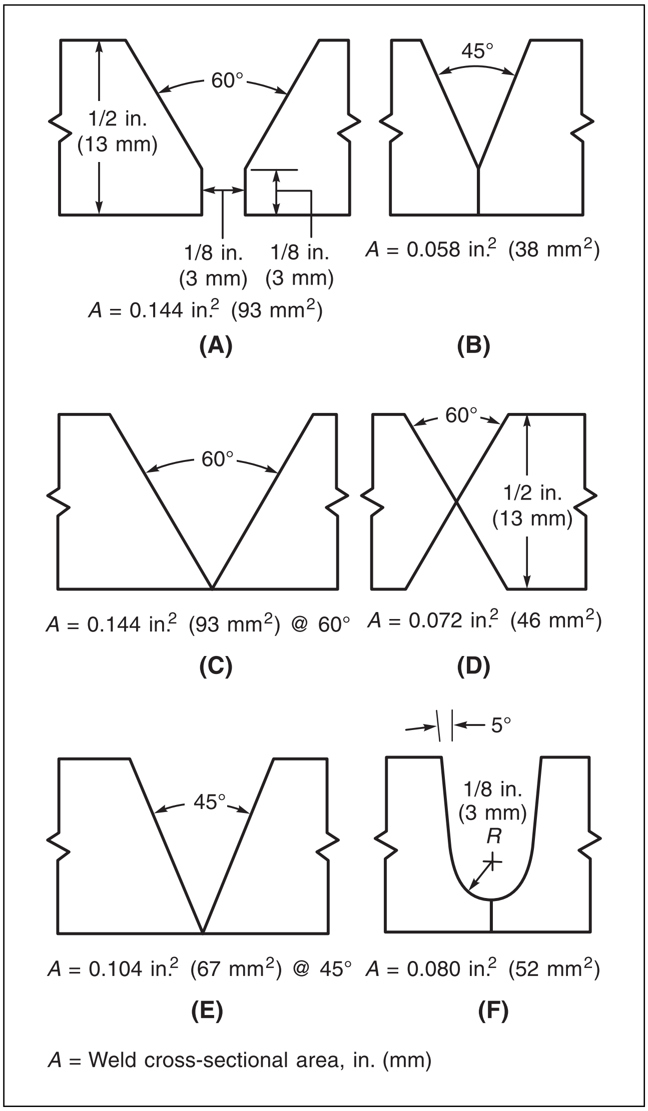


Figure 12.21—Effects of Minor Changes in Joint Design on Weld Cross-Sectional Area (*A*): (A) Typical High-Volume Weld Joint; (B) Reduced Weld Volume by Eliminating the Root Gap; (C) Another High-Volume Weld Joint; (D) Double-Sided joint for Reduced Volume; (E) Reduced Weld Volume by Decreasing the Included Angle; and (F) U-Groove for Reduced Weld Metal Volume

the components of the assembly improves. Welding speed increases with joint consistency, and weld automation becomes possible. Thermal machining centers can revolutionize manufacturing operations by improving weld joint design and eliminating operations (e.g., manual layouts). Hole patterns, alignment marks, protrusions, slits, or slots can easily be added. Some machines, particularly lasers, can etch layout patterns. All of these features save tremendous time with respect to downstream processes.

Weld root openings are often 50% to 100% of the material thickness. Controlling the size of root openings is an efficient method to improve weld penetration and consistency and thus increase weld quality. A consistent root opening can be created by designing standoffs into workpieces. Weld standoffs are used to increase weld penetration and travel speed. They also reduce weld joint preparation time when they can eliminate the beveling on workpieces, which is an expensive, labor-intensive operation. The use of computer-numerical-control (CNC) thermal machining to create these standoff features generates a cost reduction because the cost of incorporating this feature into the component is less than the savings realized from the improvement.

Figure 12.22 demonstrates the manner in which standoffs increase consistency and weld quality and reduce set-up time in welding operations, thus yielding significant cost reductions.

Figure 12.23 illustrates the manner in which weld length and spacing for intermittent welds can be designed into workpieces, thereby reducing or eliminating layout and measurement time. The addition of weld-locating features of the correct length and spacing clearly conveys the design requirements to the welder. Large cost reductions are achieved by eliminating preweld layout, postweld inspection measurements, and overwelding.

Figure 12.24 shows the manner in which a slot incorporated into the design indicates the weld location and length to the welder and the inspector.

Mistake-Proofing

A goal of all manufacturing concerns is to make manufacturing operations mistake-proof. Mistake-proofing reduces scrap costs and boosts efficiency. Figure 12.25 presents an example of the cutting of slots and tabs to allow for quick fit-up operations. If multiple noninterchangeable components are to be welded, differently keyed patterns can be used to create an assembly that, in effect, inspects itself because it cannot be assembled incorrectly. Self-inspecting workpieces can eliminate steps in the inspection process, thus reducing costs.

Process Selection

Each welding process in commercial use has areas of application providing economic advantages. These areas are broad and overlap considerably, especially with respect to the consumable electrode arc welding processes. Many fabricators have production capacity for several welding processes. Choosing the most efficient welding process for each application is vital to

Figure 12.22—Weld Standoff Thermally Machined into the Workpiece Creates a Consistent Root Opening

Figure 12.24—Slot Designed into Workpiece Clearly Identifies the Weld Location and Size without Operator Layout

Figure 12.23—Weld Length and Spacing Designed Into a Component to Reduce Layout Time

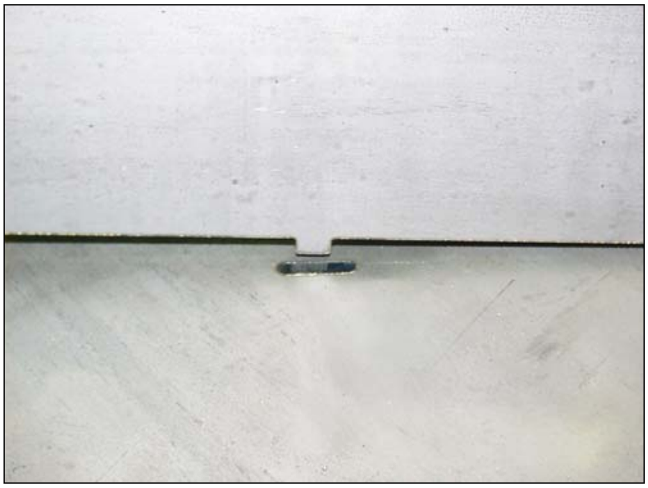


Figure 12.25—Slots and Tabs Used to Make Assembly Mistake Proof and Eliminate Workpiece Location Errors

minimizing welding costs.[9] The characteristics and advantages of the consumable electrode arc welding processes are shown in Table 12.22.

9. An overview of welding processes is presented in Chapter 1 of this volume. Welding processes are discussed in greater detail in O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of the *Welding Handbook*, 8th ed., Miami: American Welding Society.

The selection of the best welding process for a given application depends on the requirements of the job. To a degree, the processes an enterprise chooses determine the type of products that can be produced competitively. The optimum process is that which fabricates weldments at the lowest cost while producing acceptable quality at high deposition rates and with high operator factors.

Table 12.22
Characteristics and Advantages of Consumable Electrode Arc Welding Processes

Process	Characteristics and Advantages
Shielded metal arc welding (SMAW)	Flexible, all-position process; low initial cost; portable; large variety of filler metals available with special characteristics (high deposition, fast travel speed, good fillet weld contour, deep penetration); requires slag removal.
Gas metal arc welding (GMAW)	Relatively flexible; requires wire feeder and external gas; needs a special power source for all-position capability; higher deposition rates than SMAW; no slag; can be adapted to mechanized, automated, and robotic welding.
Flux cored arc welding (FCAW)	Relatively flexible; requires wire feeder; electrodes may or may not require external gas; all-position capability without special power source; higher deposition rate than SMAW and GMAW; can be adapted to mechanized, automated, and robotic welding; requires slag removal.
Submerged arc welding (SAW)	Flat and horizontal position only, but has very high deposition rate (must be mechanized for highest deposition rates); uses high-current power sources, heavy-duty wire feeders, and welding head or workpiece manipulators, which are high capital-cost items; mechanized SAW process is high quality, low-cost; flux is required; requires removal of slag and excess flux.

The deposition rates of the shielded metal arc welding (SMAW), gas metal arc welding (GMAW), flux cored arc welding (FCAW), and submerged arc welding (SAW) processes are shown in Figures 12.2 through 12.6. When large quantities of weld metal are required, the operator factor normally increases with increasing mechanization, as shown in Figure 12.26.

The submerged arc welding process is the most efficient fusion welding process in plate and structural work such as shipbuilding, bridge building, and pressure vessel fabrication, assuming the workpieces can be properly positioned and the equipment can be accurately guided. However, when welds must be made out of position or when several short welds are required on many pieces involving frequent moves of the welder or the workpiece, a flexible process such as shielded metal arc welding, gas metal arc welding, or flux cored arc welding should be employed. The optimum process is selected based on a compromise between welding speed (deposition rate), versatility (all-position), and portability (operator factor).

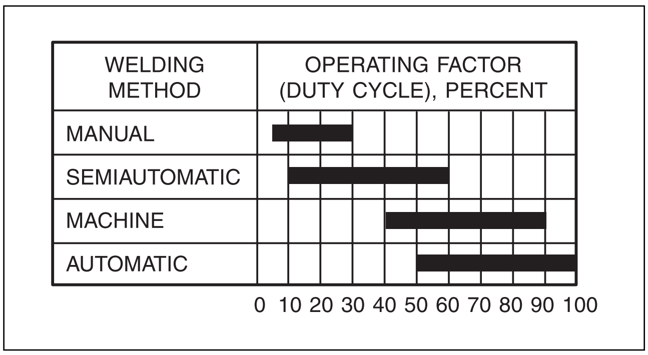


Figure 12.26—Effect of Mechanization on Operator Factor

Eliminating Operations

High-accuracy thermal machining centers can be used to eliminate many downstream operations. Machining operations as well as forming operations can be simplified and combined into all-inclusive work cells, saving time and money by reducing the number of workers handling the workpieces.

Lasers are capable of eliminating most drilling operations, including the drilling required before tapping. This eliminates the layout step. The tapping can be performed anywhere in the shop at the time of fabrication, welding, or assembly.

Production Planning

Maintaining production schedules is vital to controlling manufacturing costs in general and welding costs in particular. Therefore, the materials should be delivered in a timely manner, and appropriate equipment should be in place. The following guidelines can help prevent work delays:

1. The proper equipment for the specified welding process must be provided and set up;
2. The welding materials specified in the applicable welding procedures should be readily available at the job site;

3. Workpieces should be accurately positioned and aligned using fixtures whenever possible, and the fitup should be inspected before welding;
4. Fixtures and positioning equipment should be utilized whenever possible, as welding in the flat position greatly increases efficiency and reduces costs;
5. Power tools should be provided to remove slag and finish the weld surfaces; and
6. Work must be supervised to verify that procedures are followed, consumables are not wasted, and the workmanship is satisfactory.

Welding Procedures

Welding procedures are written instructions for shop personnel to follow in fabricating production weldments. The procedures should be thoroughly tested to verify that weldments of the desired quality are produced when the procedures are followed.

Project supervisors should select welding procedures from a portfolio of qualified procedures that best meet the requirements of the job. When selecting the welding process, the following should be considered: (1) product quality, (2) manufacturing schedule, and (3) manufacturing cost.

Supporting Activities

Production welding is normally preceded by preassembly, cleaning, and fitting. It is often followed by cleaning, machining, or painting, or all of these. Cost control is a cooperative effort, and the support of all departments is required. Implementing the following guidelines can help reduce overall manufacturing costs:

1. Workpieces should be prepared as accurately as needed, particularly those that are bent or formed to shape;
2. Workpiece preparation should entail shearing or blanking whenever possible, as these techniques may be more economical than thermal cutting if the shapes are simple;
3. All cut workpieces should be accurately and clearly marked with the job and workpiece identities;
4. Delivery of materials should be scheduled so that all components of an assembly are available as needed at the fitting area;
5. All workpieces should be inspected for accuracy before they are delivered to the fitting area;
6. Workpieces must be accurately fitted;
7. Automated or robotic equipment should be used when available and suited to the job;
8. Excessive use of temporary welded restraints or other fitting aids that have to be removed by gouging and grinding should be avoided;
9. Tack welds should be placed in grooves or in fillet locations and should be small enough to be consumed by the production weld;
10. After welding, all slag, spatter, and other matter should be removed from the weldment; and
11. The assembly should be inspected after each operation prior to dispatching the assembly to the next operation.

Field Welding

When a welding project combines weldments made in the shop and in the field, it is important to plan to make as many of the welds as possible within the controlled setting of the shop. Considering the many complex conditions and unknown variables encountered in field welding, the number of rejected welds and rework may be greatly reduced by performing the appropriate welds in the shop.

UNFORESEEN COSTS

One of the most frustrating outcomes of a job occurs when the costs have been estimated, the order has been received, and the product has been built, only to have the cost of the job ultimately exceed the estimate. This is especially frustrating when no clear cause can be assigned to the cost overrun. Often the problem results from failing to identify all the factors affecting cost, especially those that are not direct material or labor costs. Sometimes costs are hidden in operations that were not foreseen. This section explores various factors that can affect cost.

Quality Factors

Quality issues must be recognized as a factor in the management of welding and cutting costs. The cost of quality can be calculated and included in the cost estimate provided hidden steps or unnecessary operations are identified and evaluated.

The cost of quality is not always immediately obvious. It may be found in the scrap bin or in an unexpected repair job that occurs when a workpiece is not cut or welded according to the specifications. It may be hidden in the "built-in" rework that occurs as a result of having to manufacture weldments that are beyond the performance capabilities of the fabrication or welding equipment.

A typical example of hidden quality costs would be weld joint preparation in which the oxyacetylene cut quality is so poor that extra grinding is required in a rework operation to bring the workpiece into compliance with the dimensions, tolerances, or surface finish requirements. Another example would be the welding of a multipass joint in which grinding is required to prevent lack of fusion. Both the grinding and the metal removal and replacement require additional time and materials to complete the weld.

The production department supervisor is usually aware of these conditions and takes the appropriate corrective action. Nevertheless, the lost time and additional labor and material are not identified and may become a part of regular shop practice without the estimator's knowledge. If the costs incurred in the additional procedures have not been factored into the cost estimate, the estimate will be low.

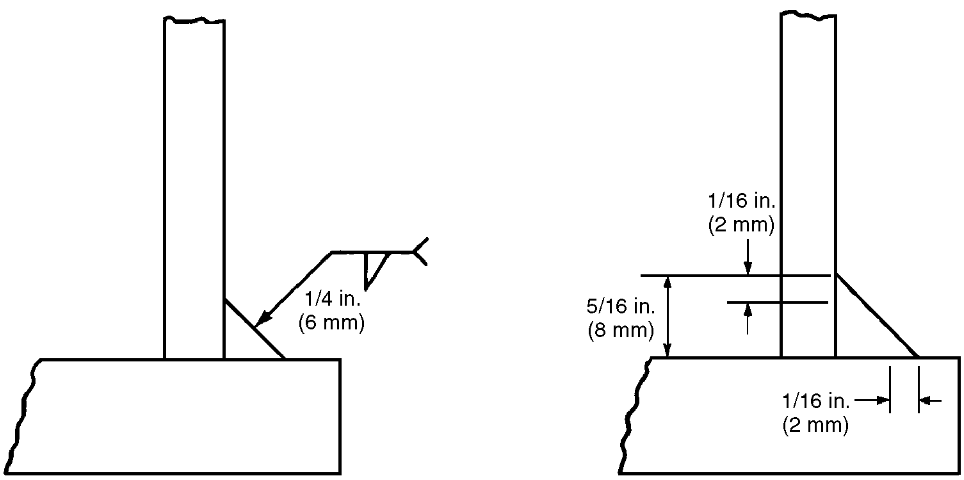
Poor workmanship also adversely affects welding costs. The cost of weld repairs can total two to three times that incurred to fabricate the original weld. Not only do repairs involve expenses for time, labor, and materials, but valuable shop space is also lost and the overall production schedule is delayed. Poor quality work may adversely affect the reputation of the manufacturer, which may ultimately be detrimental to future sales.

Overwelding

Another unforeseen cost, overwelding, results from inaccurate cutting and fitting, poor supervision, insufficient training, or lack of confidence in the strength of the weld as specified. Two joint configurations that often result in overwelding are full- or partial-penetration welds in T-joints produced in the horizontal position and butt joints fabricated between plates of unequal thickness.

Overwelding significantly contributes to excessive welding cost. The increase in weld cross section as a result of overwelding is shown in Figure 12.27. In Figure 12.28, the weld detail is shown in (A), the desired weld is illustrated in (B), and the common overwelded condition is represented in (C). Figure 12.29 illustrates the potential overwelding of a transition butt joint. Figure 12.30 illustrates the effect of poor fitup on the weld cross section.

$A_{REQ} = (0.25)^2 \cdot (0.5) = 0.03125$ $\qquad$ $A_{ACTUAL} = (0.31)^2 \cdot (0.5) = 0.048$



Overwelding a 1/4 in. (6 mm) Fillet Weld by 1/16 in. (2 mm) Increases the Area of the Weld Cross Section by 56%

Key:
A_{REQ} = Required area, in. (mm)
A_{ACTUAL} = Actual area as a result of overwelding, in. (mm)

Figure 12.27—Effect of Overwelding on a Weld Cross Section

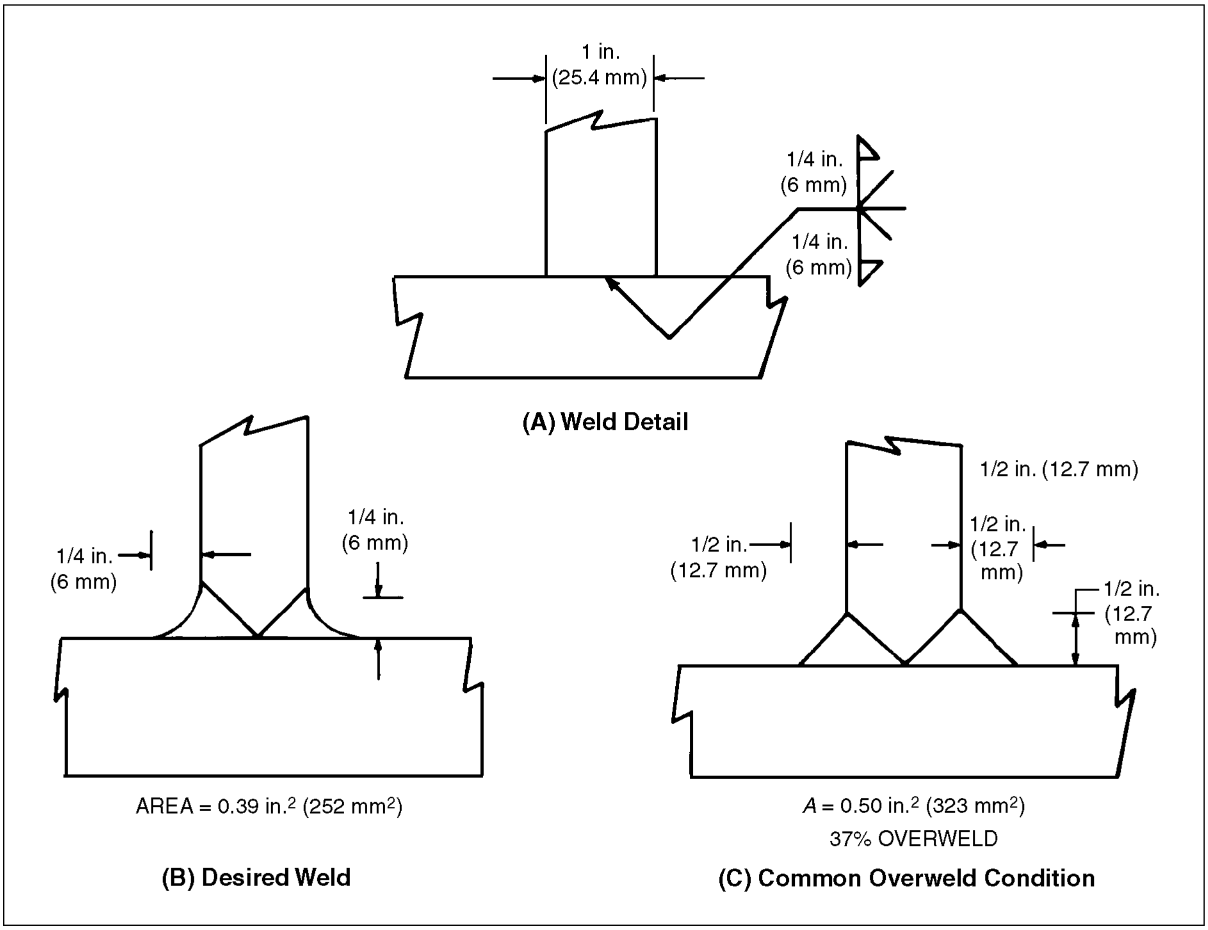


Figure 12.28—Common Overwelded Full Penetration T-Joint Fabricated in Horizontal Position: (A) Weld Detail; (B) Desired Weld; and (C) Common Overweld Condition

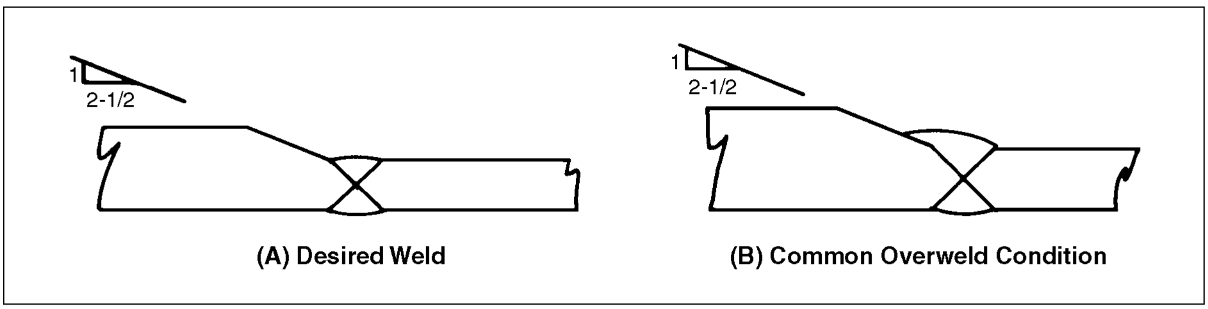


Figure 12.29—Potential Overwelding of Transition Butt Joints: (A) Desired Weld and (B) Common Overweld Condition

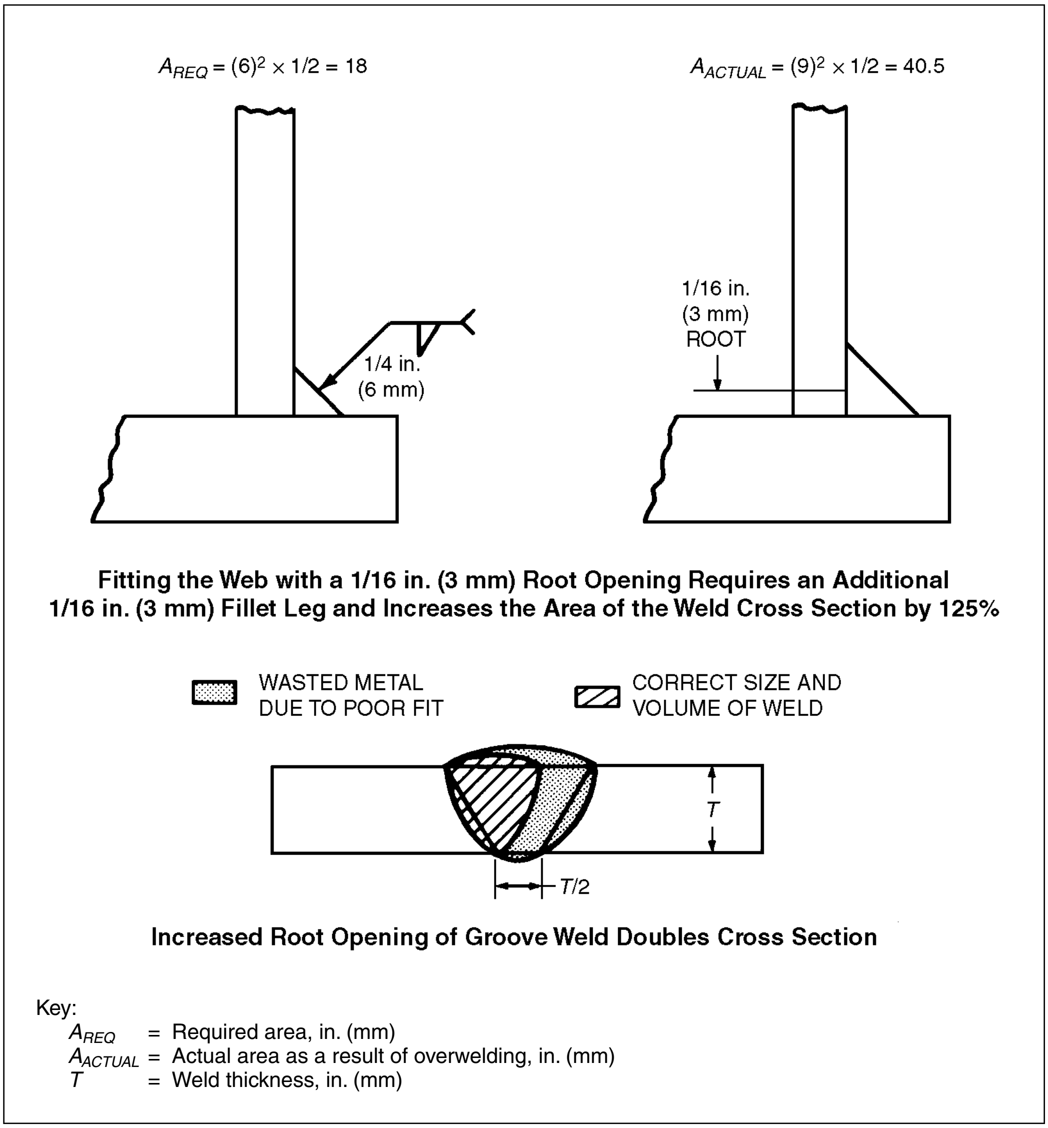


Figure 12.30—Effect of Poor Fitup on a Weld Cross Section

ECONOMICS OF BRAZING AND SOLDERING

Many of the procedures for estimating welding costs can be adapted for estimating brazing and soldering costs not only because of the similarity of the processes but also because brazing and soldering require the use of filler metal. The weight of filler metal is fundamental to the formulation of cost estimates for all these processes. However, many other variables must be considered when elaborating estimates for brazing and soldering. Some of these are similar to welding variables, whereas others are pertinent only to soldering and brazing. For example, many filler metals for brazing and soldering are costly because they contain noble or rare elements to provide desired flow and joint properties.

Table 12.23
Typical Variables for Estimating Brazing and Soldering Costs

Brazing process
Method of application (manual, mechanized, automatic)
Type of joint
Joint clearance
Length of overlap
Length of joint
Filler metal
Type
Form and size
Method of application
Brazing temperature range
Brazing flux or atmosphere
Assembly time
Loading time
Furnace brazing cycle
Heating time
Cooling time
Power or fuel requirements
Unloading time
Postbraze cleaning
Method
Time
In-process inspection
Labor rates
Filler metal cost
Flux costs
Atmosphere cost
Electric or fuel costs
Cleaning material costs

As noted in Table 12.23, numerous variables affect the cost of producing sound brazed and soldered joints. Of fundamental importance is the technique selected, which is based on the following factors:

1. Base metal,
2. Joint design,
3. Surface preparation,
4. Fixturing,
5. Flux or atmosphere,
6. Filler metal, and
7. Heating method.

These factors, singly or in combination, have a direct bearing on the costs of the operation. A correctly applied technique based on sound engineering generally results in a quality product produced at minimum cost. The goal is to heat the joint or assembly to brazing temperature as uniformly and as quickly as possible, while avoiding localized overheating. Mechanized equipment may be constructed to provide proper control of temperature, time, and atmosphere. In many cases, consideration must be given to thermal expansion of the base metal to preserve correct joint clearance while the assembly is raised to the brazing or soldering temperature.

ESTIMATING AND CONTROLLING BRAZING COSTS

To improve and control both cost and quality in brazing and soldering operations, every effort must be made to minimize the amount of filler metal used for each joint. The amount of filler metal required depends on a number of factors. Among these are joint design, fabrication technique, procedure, and the operation used to prepare and finish parts. Changes in any of these factors might improve quality and reduce costs. The typical variables used to estimate brazing costs are shown in Table 12.23.

Joint Type and Design

Two basic types of joints are used in brazing operations—the lap joint and the butt joint. Brazed joints are typically designed to accommodate shear loads, thus lap joints are preferable. Excessive overlap (greater than 4 times the thickness) in a joint leads to unnecessarily high costs due to the increased consumption of expensive brazing filler metal. Butt joints may be less expensive to fabricate, but they require costly preparation and fixturing to achieve the required critical fitup.

Many variables must be considered in designing brazed joints. From a mechanical standpoint, the joints must be capable of carrying the service loads. The rules applying to concentrated loads, stress concentration, static loading, and dynamic loading are more complex for brazed and soldered joints than they are for other machined or fabricated parts. The design of a brazed[10] or soldered joint has specific requirements that should be met. Variables of particular interest are joint clearance and chemical composition, which are discussed below.

10. Information regarding joint designs that may be adapted for brazing cost efficiency is presented in Chapter 5 of this volume.

Joint Clearance. Improper joint clearance affects costs by requiring excessive amounts of filler metal or by resulting in defective joints that need repair.

Chemical Composition. The composition of the base and filler metals and the fluxes must be compatible. The properties of the filler metal in the joint as well as the cost of the filler metal must be considered when designing for a given service condition.

Service Requirements. Mechanical performance, electrical conductivity, pressure tightness, corrosion resistance, and service temperature are design considerations that affect costs. For example, brazing an electrical connection requires a high-conductivity joint, and expensive filler metal may be needed to satisfy the requirement.

Precleaning and Surface Preparation

Clean, oxide-free surfaces are imperative to ensure acceptable brazed joints. The costs of precleaning and surface preparation generally include cleaning materials and labor. Selection of an appropriate cleaning method depends on the nature of the contaminant, the base metal, the required surface condition, and the joint design. Some materials require surface preparation such as nickel plating or light grit blasting with a suitable media to enhance surface wetting and the flow of braze alloy during thermal processing.

Assembly and Fixturing

Considering the cost of fixturing and the added processing times that fixturing entails, it is preferable to design parts that are easily assembled and self-fixturing. Some techniques that can be employed to avoid the use of fixtures include resistance tack welding; arc tack welding; interlocking tabs and slots; and mechanical methods, such as staking, expanding, flaring, spinning, swaging, knurling, and dimpling. Several self-fixturing assemblies are shown in Figure 12.31.

ESTIMATING AND CONTROLLING SOLDERING COSTS

Most of the concepts involved in estimating and controlling welding and brazing costs can be applied to soldering costs. Some of the factors discussed below apply more specifically to soldering.

Labor costs in soldering operations are essentially based on the number of worker-hours required to fabricate the joint. The implementation of automation to reduce labor costs must be carefully studied. Labor costs may or may not be reduced by the selection of an automated process. Automation must be evaluated in terms of the total cost of manufacturing, which include the purchase, installation, and maintenance of the automated system.[11]

Significant cost savings can be achieved through proper consideration during the design stage of the soldered joint. The most economical joint is designed for maximum solderability. The joint design should not only reflect fitness for purpose but also facilitate the fastest rate of soldering with the fewest discontinuities and defects. Figure 12.32 presents a schematic representation of several solder joints. These configurations can serve as the basis for joints required by a particular product.[12]

Material costs include those associated with the purchase of the solder alloys and those incurred in tooling to deliver the solder to the joint. Solder may be transferred to the joint in the form of wire, preforms, and paste. Additional costs are incurred in the purchase of the necessary consumables such as fluxing agents, soldering iron tips, and the materials required for surface preparation.[13] The amount of solder used should be carefully controlled. Too much solder is wasteful and therefore expensive; too little solder may lessen joint strength and create voids that are subject to corrosion, thus adding to the number of rejected joints that must be reworked or discarded.

For production soldering, cost control begins with the development of the soldering process best suited to the product. This involves the following three steps:[14]

1. Laboratory or field testing of materials to be soldered using specimens with standardized joint geometries and well-controlled conditions;
2. Prototype testing with a joint configuration similar to that of the soldered product to determine whether the joint can be soldered in the actual manufacturing process; and
3. Fabricating the actual product and evaluating it in terms of variations related to the inherent properties of the materials and the parameters of the soldering process.

The objective of these evaluations is to document the parameters and assess the incidence of discontinuities and defects. Performing these steps in the order specified above has cost advantages. If the first two steps are omitted to eliminate the time and cost required to perform them, the result is often even more expensive

11. Vianco, P. T., 1999, *Soldering Handbook,* 3rd ed., Miami: American Welding Society, p. 107.
12. See Reference 11.
13. See Reference 11.
14. Vianco, P. T., 1999, *Soldering Handbook*, 3rd ed., Miami: American Welding Society, p. 320.

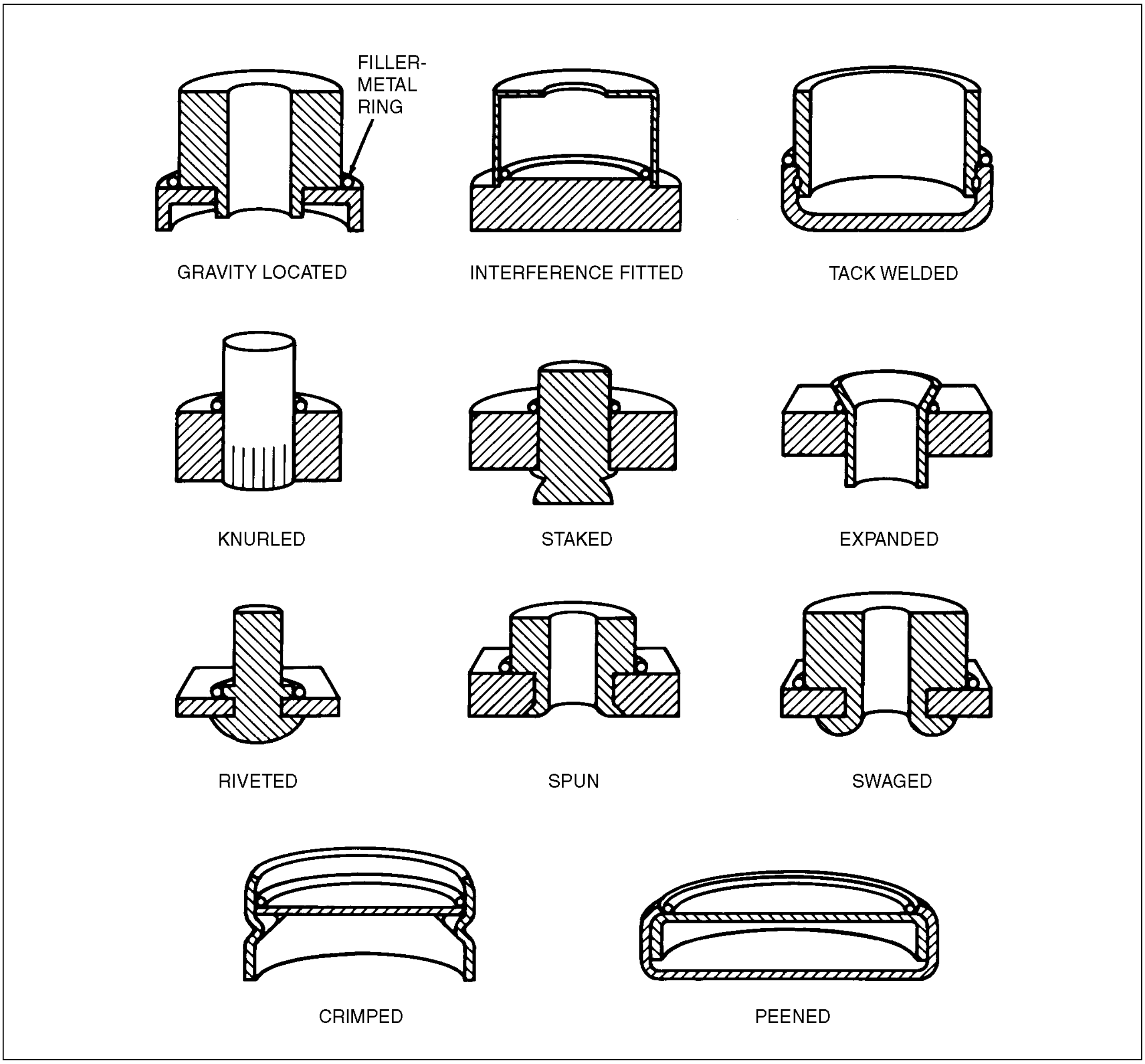
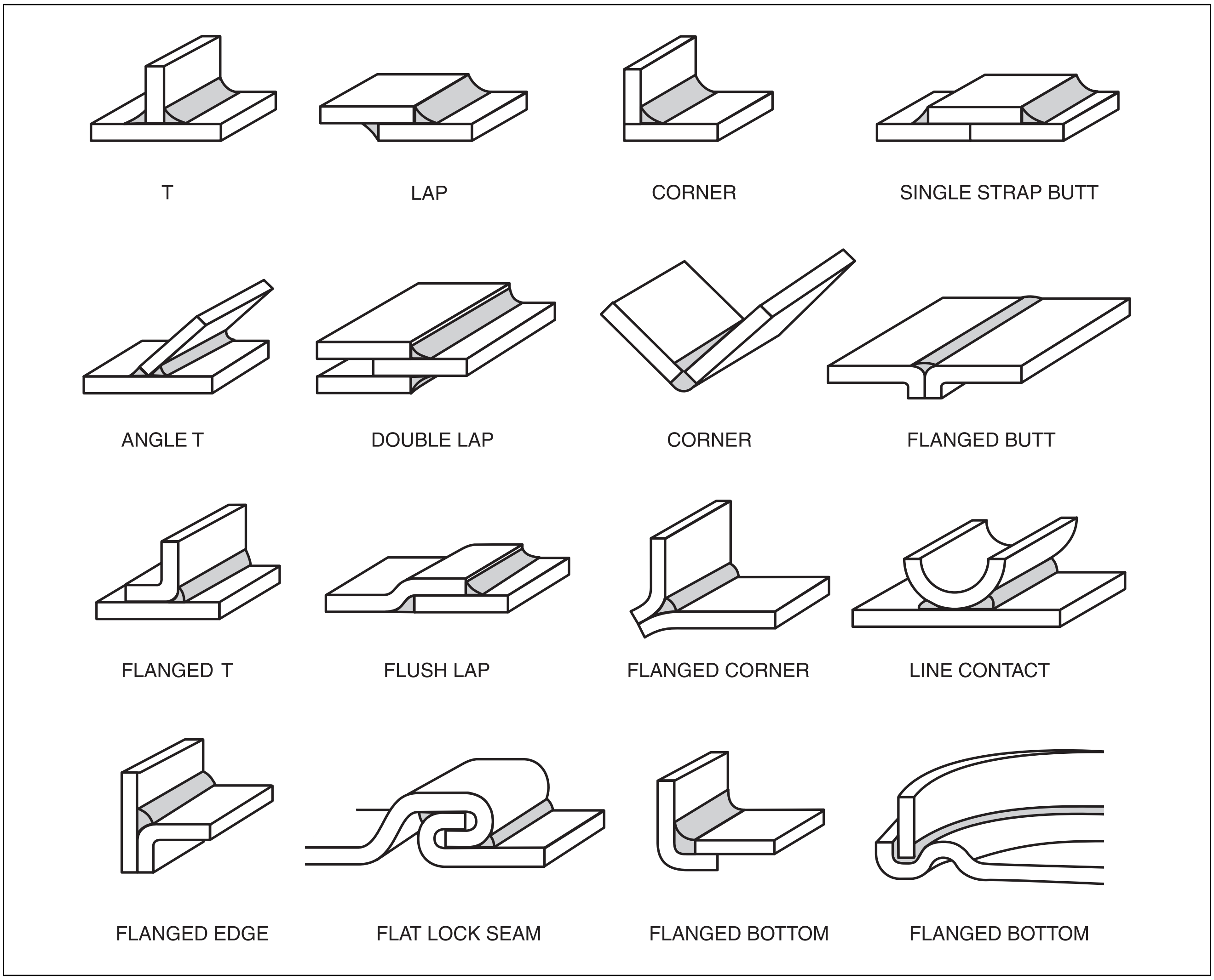


Figure 12.31—Typical Self-Fixturing Methods for Brazed Assemblies

because of production delays, increased scrap, and the need for failure analysis and reworking.

The first step eliminates combinations of base metals, solders, fluxes, and surface preparations that do not perform well, while the second verifies the parameters of the soldering and manufacturing processes, including assembly, method of introducing solder and flux, and means of heating. The results of solderability tests assure that the solder wets and spreads on the selected base material surfaces. These tests can determine whether the solder is compatible with the fluxes being considered for the project; whether alternative substrate materials, finishes, and solder temperatures can be considered; and whether pre-cleaning methods are effective.

Mechanical tests appropriate to the product's intended service may be conducted to evaluate various soldered joints. Corrosion tests may also be performed. The third step involves the examination of the finished



Source: Vianco, P. T., 1999, *Soldering Handbook*, 3rd ed., Miami: American Welding Society, Figure 1.92.

Figure 12.32—Several Fundamental Soldered Joint Configurations

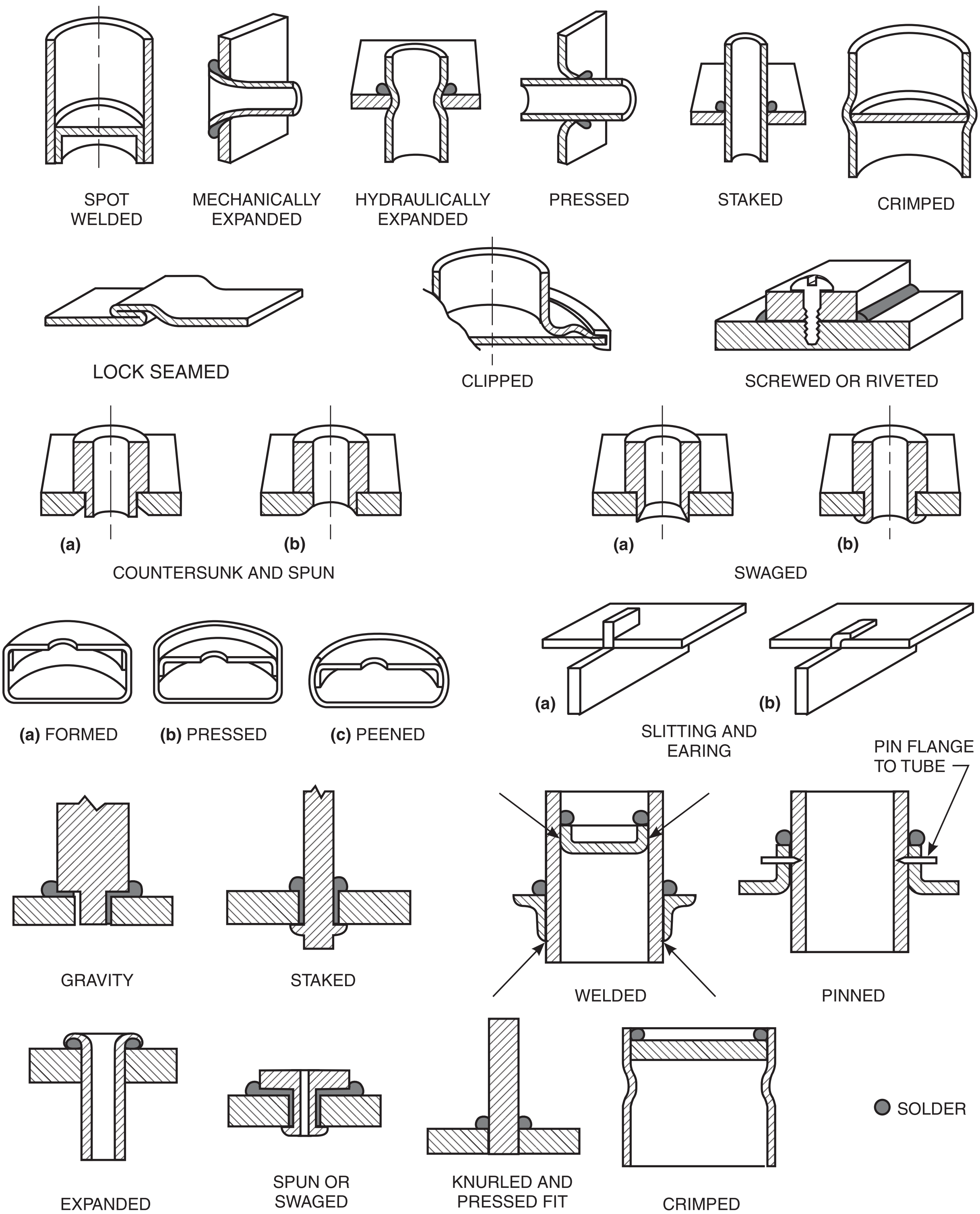
product to determine the incidence and types of discontinuities or defects it may have as a result of the soldering process parameters and identify any damage to the joint that may have occurred during postsoldering fabrication. This evaluation determines whether the product meets pre-established specifications.[15]

Self-fixturing designs such as those illustrated in Figure 12.33 save assembly time and often preempt the purchase of fixturing equipment.

Hand soldering may be cost-effective for unusual workpiece geometries that may require expensive fixturing for production lines. While hand soldering is often viewed as inefficient when compared to modern manufacturing processes, this technique is flexible and versatile and sometimes the most economical option. It should be considered when the quantity of products is too small to justify the purchase of automated equipment. Quality can be more consistent because operators inspect as they work, identifying and correcting problems as they occur.

In production runs, a large number of defective joints might be produced before the problem is discovered,

15. Vianco, P. T., 1999, *Soldering Handbook*, 3rd ed., Miami: American Welding Society, pp. 320–322.



Source: Vianco, P. T., 1999, *Soldering Handbook*, 3rd ed., Miami: American Welding Society, Figure 1.98.

Figure 12.33—Self-Fixturing Techniques Used in Soldered Joint Design

and these would have to be scrapped or repaired. When dissimilar metals or dissimilar thicknesses of metal are involved, the temperature can be controlled manually so that both pieces are heated adequately.

ECONOMICS OF THERMAL CUTTING

The procedures used to estimate welding costs can be adapted to estimate thermal cutting costs because the processes are similar in many respects. Oxyfuel cutting and oxyfuel welding, as well as plasma arc cutting and plasma arc welding, share most variables except for filler metal consumption.

ESTIMATING COSTS

Oxyfuel gas (OFC) and plasma arc cutting (PAC) are commonly used for the shape cutting of workpieces from sheet and plate metals.[16] Oxyfuel gas cutting is generally limited to the cutting of carbon and low-alloy steels. Special process modifications are required to cut high-alloy steels. Plasma arc cutting can be used to cut any metal. Most plasma arc cutting applications involve carbon steel, aluminum, and stainless steel. Both processes can be used for plate beveling, shape cutting, and piercing.

Both the oxyfuel gas and plasma arc cutting processes can be operated manually or used with portable machine cutting equipment. However, the plasma arc cutting process requires a special power source, and plasma arc cutting torches are usually larger and heavier than oxyfuel gas cutting torches. As a result, when either oxyfuel gas cutting or plasma arc cutting are applicable, oxyfuel gas cutting is often preferred in both manual and portable machine cutting applications.

The shape cutting machines used for plasma arc cutting and oxyfuel gas cutting are similar in design. Generally, plasma arc shape cutting machines can cut at higher speeds than similar oxyfuel gas cutting machines.

Carbon steel plate under 3 in. (75 mm) thick can be cut faster with plasma arc cutting than with oxyfuel gas cutting when the appropriate equipment is used. For thicknesses less than 1 in. (25 mm), plasma arc cutting speeds can be up to five times faster than those for oxyfuel gas cutting. When the base metal is over 1-1/2 in. (38 mm) thick, the selection of plasma arc cutting or oxyfuel gas cutting depends on other factors such as equipment costs, the load factor, and whether the equipment is to be used to cut thinner steel plates and nonferrous metals.

The capital costs for oxyfuel gas cutting equipment are relatively low compared to those for plasma arc cutting equipment. The highest cost item for plasma arc cutting equipment is the power source. Large, high-voltage power sources are required to cut thick plate. Because plasma arc cutting's speed advantage over oxyfuel gas cutting decreases with increasing plate thickness, plasma arc cutting stations are usually delegated to plate thickness less than 1 in. (25 mm), and oxyfuel gas cutting is used on thicker plates.

The economic advantages of plasma arc cutting over oxyfuel gas cutting are exploited best in multiple-torch, numerically or optically controlled cutting machines. Plasma arc cutting is used in high-volume stations in large fabrication plants, service centers, shipyards, and other facilities in which large quantities of cut material are required.

High-capacity plasma arc cutting machines are often equipped with water tables. The use of water tables improves the cut quality and reduces the smoke and glare associated with plasma arc cutting in ambient air, although it further increases the initial capital expenditure.

CONTROLLING COSTS

Besides performing the obvious functions of facilitating bids or requests for quotes, estimates can also serve as the first planning step in controlling costs. During the course of developing a cost estimate, an overview or outline of the essential variables affecting the costs must be taken into account. To address these variables, a general understanding of the welding or cutting procedure, method, or sequence of operations is necessary. From this foundation comes the more detailed development of procedures, methods and sequences that are needed to fabricate the job following a successful bid.

Implementing the plan developed during the estimating stage requires follow-up during the course of the job. Without this follow-up, all efforts at controlling costs within the expectations developed during the estimating stage could be lost. The most successful form of follow-up is an auditing, monitoring, and reporting system. Such a system involves monitoring by supervisors and lead personnel to ensure that welders and welding operators are following the procedures and methods as planned. In addition, the auditing of all plans developed for the estimated job is carried out by manufacturing engineering or quality assurance personnel to prevent noncompliance with the plan. In this way, the quality and cost results of a job can be compared to the expectations developed during the estimate, and effective cost control can be maintained.

16. For more detailed information on oxyfuel gas cutting and plasma arc cutting, see O'Brien, R. L., ed., 1991, *Welding Processes*, Vol. 2 of *Welding Handbook*, 8th ed., Miami: American Welding Society.

CONCLUSION

The information presented in this chapter is intended to serve as a guideline. Each job estimate contains elements that deviate from the data given here and therefore may have to be modified or extrapolated. In most cases, detailed information on the cost of welding, brazing, soldering, or cutting is well developed because a significant amount of research is dedicated to this phase of the estimate.

This information defines the amount of time consumed by the various processes to produce welds during the arc-on time. However, arc-on time accounts for only a portion of the time a welder or operator spends in making welds. The remainder of this time is nonarc time, but it is a part of the total cycle time and in most cases, can constitute the bulk of time consumed in generating welds.

The operator factor given in this chapter should provide the estimator a good idea of the arc-on versus the nonarc time for any given welding process. The estimator should find it beneficial to use this operator factor as a starting point and then ascertain the operator factor for the operations in question. In many manufacturing plants, the operator factor for semiautomatic welding processes has been found to be approximately 15%. If, as shown in Table 12.15, the operator factor could be raised to 30% or above, which is an achievable goal, the cost of welding would be cut in half. The importance of both the arc-on time and the nonarc time should be kept in perspective when using the information presented in this chapter in making cost estimates.

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CHAPTER 13

WELD QUALITY

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CHAPTER 13

WELD QUALITY

INTRODUCTION

Weld quality is an area that requires attention in every phase of the manufacturing and service life of welded, brazed, and soldered assemblies. The process begins with a design that properly addresses the service life requirements for the product as well as manufacturing requirements. Next, manufacturing and construction factors must be considered, which include the selection of joining processes, materials, and filler metals; the establishment of welder and operator performance qualifications; and the selection of the methods and frequency of inspection and nondestructive examination.

Due to our increased expectations of components in service, efforts to fabricate weldments that are stronger and lighter and have higher performance threshold limits are at the forefront of industry. The risks associated with loss of service, maintenance and repair, replacement, and other liabilities are so great that an adequate quality control program is ultimately very affordable. Thus, at the heart of weld quality is the understanding of the occurrence of discontinuities, their significance, methods of examination, detectability, and correction.[1]

This chapter presents an overview of the discontinuities associated with welding, brazing and soldering. Descriptions of the discontinuities are included, along with a discussion of their common causes and remedies. A process-specific discussion is beyond the scope of this chapter; the reader is encouraged to consult *Welding Processes*,[2] Volume 2 of the *Welding Handbook*, 8th edition, for further information on the weld discontinuities applicable to a particular process.

DEFINING WELD QUALITY

Weld quality relates directly to the integrity of weldments. If a weldment, brazement, or soldered joint is to have the required reliability throughout its life, it must exhibit a sufficient level of quality and fitness for purpose. Quality includes design considerations, which means that each weldment should be:

1. Adequately designed to meet the intended service for the required life;
2. Fabricated with specified materials and in accordance with the design standards; and
3. Installed, operated and maintained within the stress, fatigue, and corrosion design limits.

Both economic and safety considerations influence weld quality. Economic considerations require that a product be competitive in the market, while safety requires that the product function without presenting a hazard to people or property. In order to perform at the intended levels for the required service life, weldments and brazements must be adequately designed. They must be fabricated with the materials specified in accordance with accepted design standards, and they must be operated and maintained properly.

Although weld quality considerations are often narrowly confined to the physical features normally examined by inspectors, quality also includes such factors as hardness, chemical composition, and mechanical properties. All of these characteristics contribute to the fitness for purpose of a weld. The quality level required to provide the desired reliability depends on the expected modes of failure under the anticipated service conditions.

"Quality" is both a qualitative and a quantitative term and is often used in a relative manner to address the perceived need to improve a product. To require higher quality standards than are needed for an application is not only unnecessary but also economically imprudent. Therefore, quality levels are permitted to vary among different weldments and individual welds, depending on the quantitative aspects of their design requirements.

The majority of welded fabrication standards define quality requirements to ensure safe operation in the intended service. The stipulations in these standards are to be considered minimum requirements, and the accep-

1. Inspection methods and procedures for detecting discrepancies in welded and brazed joints are discussed in Chapter 14.
2. O'Brien, R. L., ed., 1991, *Welding Processes*, Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

tance criteria for welds should not be breached without the benefit of sound engineering judgment. For critical applications, more stringent requirements than those specified in the fabrication standard may be necessary to ensure safety.

Weld quality can be verified by nondestructive examination (NDE). Acceptance standards for welds are generally related to the method of NDE used in their inspection. All deviations from the acceptable limits require evaluation. The acceptance or rejection of a weld is based on well-defined conditions. Repair of unacceptable or defective conditions is normally permitted so that the quality of the weld may be brought up to acceptance standards.

Quality requirements are specified by codes, standards, specifications, and regulations that are based on rational assessments concerning economics, performance, and safety. It is important to note that many standards relating to weld quality do not govern product usage. They also leave the maintenance of the fabricated product up to the owner's discretion. Consequently, the user or a designated engineering representative must modify, amplify, or impose additional weld quality standards during maintenance activities to ensure that the product functions properly. The owner or the owner's engineering representative may modify the documents to reflect additional concerns of usage related to safety or economics, or both. Welds are examined with regard to size, shape, contour, soundness, and other features.[3]

DETERMINATION OF QUALITY REQUIREMENTS

The primary criteria affecting the selection of quality requirements are design, fabrication, inspection, operation, maintenance, and economics. The determination of the overall quality requirements for weldments, brazements, or soldered joints is a major consideration involving design teams and quality groups. Specifying excessive quality can lead to high costs with few benefits, but specifying low quality weldments can lead to high maintenance costs and an excessive number of failures. Thus, the aim is to specify features that lead to fitness for service.

Fortunately, valuable guidance in determining the desired level of weld quality is provided in fabrication codes and standards. These often indicate allowable levels of stress and permissible discontinuities. These codes and standards are based on material properties, fabrication experience, nondestructive examination results, failures, and research. On the whole, they have been proven to promote the production of safe, reliable welds.

The optimum quality required for a weldment is determined by considering the following factors:

1. Cost of design, materials, fabrication, and quality assurance;
2. Cost of a possible failure multiplied by the probability of failure; and
3. Maintenance and repair costs.

It is important to note that the lowest fabrication cost seldom represents the lowest total cost.

Design Considerations

Fitness for service requires that the design of a weldment or structure be consistent with sound engineering practices.[4] Of crucial importance is the determination of the loading conditions to which the weldment will be subjected. Components and welds of adequate size must be specified to ensure that stresses from anticipated service loads are not excessive. The intended service should be carefully analyzed to determine whether cyclic loading might result in fatigue failure in highly stressed members. If the anticipated number of fatigue loading cycles exceeds 10,000, the possibility of fatigue failure for critical members should be considered.

Environmental conditions during the intended service should be understood and incorporated into the design. For example, brittle fracture is a possibility in low-temperature service. Conversely, creep is a consideration in high-temperature service. Furthermore, corrosion and wear can reduce the section size and increase service stresses, as well as create sites for fatigue or stress corrosion cracks to initiate, which further reduce fitness for service of the assembly. In severe situations, a fracture mechanics analysis or finite element stress analysis, or both, should be performed.

Designers must select materials of the proper size that have the appropriate chemical and mechanical properties to ensure satisfactory service. If a material that meets all of the requirements is not available, other means of providing fitness for service have to be specified. For example, in a highly corrosive environment, suitable solutions may be to paint or apply a coating to the metal surfaces or provide cathodic protection.

Fabrication Considerations

The contractor should select fabrication procedures and practices which ensure that the weldments meet the design specifications. The fabrication procedures

3. Inspection methods and procedures for detecting discrepancies in welded and brazed joints are discussed in Chapter 14.

4. For additional information on design considerations, see Chapter 5, "Design for Welding."

must be rigorously adhered to and followed by inspection and NDE to verify that the weldments are free from unacceptable discontinuities.

Inspection Considerations

Inspection and NDE methods vary, depending on the contractual requirements or design specifications, intended service, material type, and size. For a simple fillet weld in mild steel, visual inspection may suffice to ensure that the base metal is free of surface contaminants and the weld meets the specified requirements. However, for a thick-plate joint, while visual inspection detects surface impurities and mill scale, ultrasonic examination is needed to ensure that the plate is free of laminations prior to welding. The completed weld usually has other NDE requirements to ensure the soundness of the joint. It is important to note that since only the exposed surfaces of certain welds can be inspected, a sufficient margin of safety must be incorporated in the design to allow for the possibility of undetected discontinuities.

Operating and Maintenance Considerations

Weld quality is not restricted to the initial completion of a weld in the fabrication or construction of a weldment. It also encompasses economic concerns related to the ongoing operation of weldments, subassemblies, and completed facilities. Weld quality is an integral aspect of the safe operation of power plants; dams; and petrochemical, industrial, and commercial facilities. It is also vital to welded consumer and commercial products such as automobiles, trucks, railroads, airplanes, ships, pipelines, and bridges. These must not only be built correctly, but must be maintained for safe, reliable, and economic service to the owners and the general public.

Operating a facility safely requires periodic inspection. If failure at a facility would result in a public hazard or the destruction of property, inspections should be more frequent and more rigorous. Power plants, chemical plants and refineries, dams, and bridges are examples of fixed facilities that may be hazardous to facility employees, the public, and the surrounding neighborhoods if a failure should occur.

Some facilities can continue operations during inspection and maintenance while others may require a complete shutdown. Often the loss of production is far more expensive than the direct cost of the repair. In such cases, premium materials and costly fabrication practices can easily be justified, provided these precautions permit extended operating periods between inspections or improve the likelihood that extensive repairs are not required as a result of periodic inspections.

Examples of how industry has addressed these issues are (1) ASME *Boiler and Pressure Vessel Code*[5,6] requirements for in-service inspection and maintenance of power plants and vessels, (2) regulatory oversight in accordance with the *National Board Inspection Code*, NB-23,[7] and (3) American Petroleum Institute standards for the inspection and repair of petrochemical plants, tanks, and pipelines.

OVERVIEW OF WELD DISCONTINUITIES

In the American Welding Society publication *Standard Welding Terms and Definitions*, AWS A3.0:2001, the term *discontinuity* is defined as "an interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics."[8] It should be noted that a discontinuity is not necessarily a defect. A defect is defined as "a discontinuity or discontinuities that by nature or accumulated effect render a part or product unable to meet minimum applicable acceptance standards or specifications"[9] or a flaw, which is defined as "an undesirable discontinuity.[10]

A summary of the types of discontinuities associated with various welding processes is presented in Table 13.1.[11] The weld discontinuities associated with specific

5. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, *Boiler and Pressure Vessel Code*, New York: American Society of Mechanical Engineers.
6. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
7. The National Board of Boiler and Pressure Vessel Inspectors, *National Board Inspection Code*, NB-23, Columbus, Ohio: The National Board of Boiler and Pressure Vessel Inspectors.
8. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society, p. 27.
9. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society, p. 26.
10. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society, p. 36.
11. The terminology used in this chapter is based on American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society.

Table 13.1
Discontinuities Commonly Associated with Welding Processes

Welding Process	Discontinuity* Porosity	Inclusions	Incomplete Fusion	Incomplete Joint Penetration	Undercut	Overlap	Cracks
Arc Welding Processes							
Stud welding (SW)	—	x	x	—	x	—	x
Plasma arc welding (PAW)	x	x	x	x	x	—	x
Submerged arc welding (SAW)	x	x	x	x	x	x	x
Gas tungsten arc welding (GTAW)	x	x	x	x	x	x	x
Gas metal arc welding (GMAW)	x	x	x	x	x	x	x
Flux cored arc welding (FCAW)	x	x	x	x	x	x	x
Shielded metal arc welding (SMAW)	x	x	x	x	x	x	x
Carbon arc welding (CAW)	x	x	x	x	x	x	x
Resistance Welding Processes							
Resistance spot welding (RSW)	x†	x	x	x	—	—	x
Resistance seam welding (RSEW)	x†	x	x	x	—	—	x
Projection welding (PW)	—	—	x	x	—	—	x
Flash welding (FW)	—	—	x	x	—	—	x
Upset welding (UW)	—	—	x	x	—	—	x
Percussion welding (PEW)	—	—	x	—	—	—	x
Oxyfuel Gas Processes							
Oxyacetylene welding (OAW)	x	x	x	x	x	x	x
Oxyhydrogen welding (OHW)	x	—	x	x	—	—	x
Pressure gas welding (PGW)	x	—	x	—	—	—	x
Solid-State Processes‡							
Cold welding (CW)	—	—	x	—	—	—	x
Diffusion welding (DFW)	—	—	x	—	—	—	x
Explosion welding (EXW)	—	—	x	—	—	—	—
Forge welding (FOW)	—	—	x	—	—	—	—
Friction welding (FW)	—	—	x	—	—	—	—
Ultrasonic welding (UW)	—	—	x	—	—	—	—
Other Processes							
Electron beam welding (EBW)	x	—	x	x	—	—	x
Laser beam welding (LBW)	x	—	x	x	—	—	x
Electroslag welding (ESW)	x	x	x	x	x	x	x
Induction welding (IW)	—	—	x	—	—	—	x
Thermite welding (TW)	x	x	x	—	—	—	x

* The symbol “x” indicates that the type of discontinuity may occur in welds produced by the process. The symbol “—” indicates that the occurrence of this type of discontinuity in these welds is very rare.
† In resistance welds, “porosity”” is more properly termed “voids.”
‡ As these are not fusion processes, the appropriate term for “incomplete joining” is “incomplete welding” rather than “incomplete fusion.”

Source: Adapted from American Welding Society (AWS) Committee on Methods of Inspection, 1999, *Guide for the Nondestructive Examination of Welds*, ANSI/AWS B1.10:1999, Miami: American Welding Society, Table 2.

welding processes are covered in more detail in *Welding Processes*,[12] Volume 2 of the *Welding Handbook*, 8th edition.

DISCONTINUITIES ASSOCIATED WITH FUSION WELDING

The term *fusion welding* is used to describe the group of welding processes that utilizes the melting of a base metal or of a base metal and filler metal to produce a weld. The following characteristics must be taken into consideration when identifying and evaluating fusion weld discontinuities:

1. Size;
2. Shape;
3. Acuity or sharpness;
4. Location with respect to the weld, the exterior surfaces of the joint, and the critical sections of the structure; and
5. Orientation with respect to the principal working stress and residual stress.

The American Society for Nondestructive Testing (ASNT) has a classification of discontinuity size, and the American Society for Testing and Materials (ASTM) publishes a standard addressing the size of inclusions. As a general rule, the larger the discontinuity, the more susceptible the weld is to failure.

Discontinuities are characterized not only by their size but also by their shape. Planar-type discontinuities such as cracks, laminations, incomplete fusion, and incomplete joint penetration create serious notch effects. Three-dimensional discontinuities amplify stresses by reducing the weldment area. Spherical discontinuities—usually porosity caused by the entrapment of gas during solidification—can occur anywhere within the weld. Elongated discontinuities may also appear in any orientation.

With respect to acuity and sharpness, stresses concentrate at notches, which occur at sudden changes in weldment geometry. The more severe the change in geometry, the greater the notch effect and the accompanying stress concentration. Tensile stresses perpendicular to a notch and shear stresses parallel to a notch are concentrated at the notch tip. Extremely high concentrations of stress can develop at sharp notches such as cracks.

Discontinuities associated with improper weld location are performance or procedure related. The tolerances with respect to location are specified on the drawing. The location of the weld beyond the tolerance limits constitutes a discontinuity.

With respect to their orientation, discontinuities alter stresses by means of amplification or concentration, or both. The least detrimental effect is stress amplification. Discontinuities amplify stresses by reducing the cross-sectional area. The average stress is amplified in direct proportion to the reduction in area. Stress concentration is more detrimental.

CLASSIFICATION

The discontinuities commonly found in joints produced by fusion welding can be classified into three major categories. These are related to (1) process and procedure, (2) metallurgical behavior, and (3) design. Discontinuities related to process, procedure, and design typically alter stresses in the weld or the heat-affected zone. Metallurgical discontinuities may also alter the local stress distribution as well as affect the mechanical or chemical (corrosion resistance) properties of the weld and the heat-affected zone.

The discontinuities grouped in each of the three major classifications are shown in Table 13.2. It should be noted that these groupings are somewhat fluid as the discontinuities listed in each category may have secondary origins in other categories.

Process- and Procedure-Related Discontinuities

Certain discontinuities commonly encountered in joints created with the fusion welding processes are related to specific processes.[13] For example, slag inclusions are associated with shielded metal arc, flux cored arc, submerged arc, and electroslag welding, whereas tungsten inclusions result from improper gas tungsten arc or plasma arc welding practices.

Metallurgical Discontinuities

Metallurgical discontinuities are changes in the properties of the weld or base metals.[14] Most metallurgical discontinuities are closely related to the welding process and the design of the weldment. For example, the high heat input employed in certain processes may cause segregation of alloying elements in some metals, and the welding together of incompatible materials can cause

12. See Reference 1.

13. For further information about process-specific discontinuities, refer to O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

14. Typical discontinuities associated with specific base metals are discussed in Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

Table 13.2
Classification of the Weld Joint Discontinuities that Occur in Fusion Welding

I. Process- or Procedure-Related Discontinuities		
	A. Geometric	
		Backing left on
		Burn-through (melt-through)
		Concavity
		Convexity
		Excessive weld reinforcement
		Improper reinforcement
		Incomplete penetration
		Incomplete fusion
		Mismatch
		Overlap
		Shrinkage
		Surface irregularities
		Undercut
	B. Other	
		Arc craters
		Arc strikes
		Oxide films
		Slag inclusions
		Spatter
		Tungsten inclusions
II. Metallurgical Discontinuities		
	A. Cracks or fissures	
		Cold
		Delayed
		Hot
		Lamellar tearing
		Reheat, stress-relief, or strain-age*
	B. Porosity	
		Scattered
		Cluster
		Aligned
		Piping
		Elongated
	C. Heat-affected-zone and microstructure alteration	
	D. Weld-metal and heat-affected-zone segregation	
	E. Base-metal laminations and delaminations	
III. Design-Related Discontinuities		
	A. Changes in section and other stress concentrations	
	B. Type of weld joint	

* For further information on these discontinuities, refer to Oates, W. R., ed., 1996, *Materials and Applications—Part 1*, Vol. 3 of *Welding Handbook*, 8th ed., Miami: American Welding Society; and Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of *Welding Handbook*, 8th ed., Miami: American Welding Society.

severe embrittlement. Cracks are usually caused by metallurgical discontinuities. For example, cold cracks are often the result of localized embrittlement.

Metallurgical discontinuities may also occur in the base metal prior to fabrication. For example, laminations are base metal defects. These are a type of discontinuity characterized by separation or weakness generally aligned parallel to the worked surface of a metal, possibly resulting from piping blisters, seams, inclusions, or segregations that have become elongated and made directional by working (e.g., rolling, forging, or drawing).

Design-Related Discontinuities

Some discontinuities found in welded joints are the result of design decisions. Proper weldment design ensures that the performance of the weldment is not adversely affected by stress concentrations, which may initiate a failure. For example, an abrupt change in shape or the cross-sectional area of a weldment, which concentrates stress, is a discontinuity. Weldment design can also affect the occurrence of mechanical and metallurgical discontinuities. Partial penetration is a recognized discontinuity that must be avoided in certain types of weldments.

Moreover, weldments designed with limited access for welding make it difficult for the welder to deposit a sound weld and increase the likelihood of welder-performance or process-related discontinuities. Conditions of high restraint increase the likelihood that hot or cold cracks may initiate in the weld metal or heat-affected zone.

LOCATION AND OCCURRENCE OF DISCONTINUITIES

Discontinuities in weldments may be found in the weld metal, the heat-affected zone, and the base metal. They may be surface or subsurface discontinuities, requiring the application of different inspection methods. They may be dimensional discontinuities, involving concerns with distortion, joint mismatch, and weld size, among others.

It should be noted that the term *fusion-type discontinuity* is sometimes used inclusively to describe incomplete fusion, incomplete joint penetration, inclusions, and similar elongated discontinuities in fusion welds. Although many codes and standards consider fusion-type discontinuities less critical than cracks, some specifically prohibit fusion-type defects as well as cracks.

Specific joint types and welding procedures have an effect on the type, location, and incidence of discontinuities. The welding process, joint details, restraint on the weldment, or a combination of these may have an effect on the discontinuities to be expected.

The common weld discontinuities, their typical locations, and additional remarks regarding occurrence are presented in Table 13.3. The discontinuities listed in Table 13.3 are depicted in the butt, lap, corner, and T-joints shown in Figures 13.1 through 13.6.

COMMON FUSION WELD DISCONTINUITIES

The discontinuities that are typically associated with the fusion welding processes are described below. A discussion of their common causes and remedies follows each description.

Table 13.3
Types of Fusion Weld Discontinuities

Type of Discontinuity	Location*	Remarks	Identification†	Depicted in Figure Number‡
Porosity	WM	Could also be found in BM and HAZ if BM is a casting		
Scattered	WM		1a	13.2, 13.6
Cluster	WM		1b	13.1–13.3, 13.6
Piping	WM		1c	13.2, 13.6
Aligned	WM		1d	13.1, 13.2,
Elongated	WM		1e	—
Inclusions				
Slag	WM, WI		2a	13.1–13.6
Tungsten	WM, WI		—	—
Incomplete fusion	WM, WI	WM between passes	3	13.1–13.5
Incomplete joint penetration	WM	Weld root	4	13.1–13.5
Undercut	WI	Adjacent to weld toe or weld root in BM	5	13.1–13.6
Underfill	WM	Weld face or root surface of a groove weld	6	13.1–13.3, 13.5
Overlap	WI	Weld toe or root surface	7	13.1–13.6
Laminations	BM	BM, generally near midthickness of section	8	13.1–13.6
Delaminations	BM	BM, generally near midthickness of section	9	13.1–13.6
Seam and lap	BM	Base metal surface, typically aligned with rolling surface	10	13.1, 13.3–13.6
Lamellar tear	BM	BM, near HAZ	11	13.3, 13.5
Cracks (including hot and cold cracks)				
Longitudinal	WM, HAZ, BM	WM or BM adjacent to WI	12a	13.1–13.6
Transverse	WM, HAZ, BM	WM (may propagate into HAZ and BM)	12b	13.1–13.6
Crater	WM	WM at point where the arc is terminated	12c	13.1–13.6
Throat	WM	Parallel to the weld axis. Through the throat of a fillet weld.	12d	13.1–13.6
Root	WI, HAZ	Root surface or weld root	12f	13.1–13.6
Toe	WI, HAZ		12e	13.1, 13.4–13.6
Underbead and HAZ	HAZ	BM in HAZ	12g	13.1, 13.2, 13.4–13.6
Concavity	WM	Weld face of a fillet weld	—	—
Convexity	WM	Weld face of a fillet weld	—	—
Weld reinforcement	WM	Weld face of a groove weld	—	—

* WM = weld metal; WI = weld interface; BM = base metal; and HAZ = weld heat-affected zone.
† These identification numbers are used in Figures 13.1 through 13.6.
‡ Refer to Figures 13.1 through 13. 6 for an illustration of the discontinuity.

Source: Adapted American Welding Society (AWS) Committee on Methods of Inspection, 1999, *Guide for the Nondestructive Examination of Welds*, ANSI/AWS B1.10:1999, Miami: American Welding Society, Table 1.

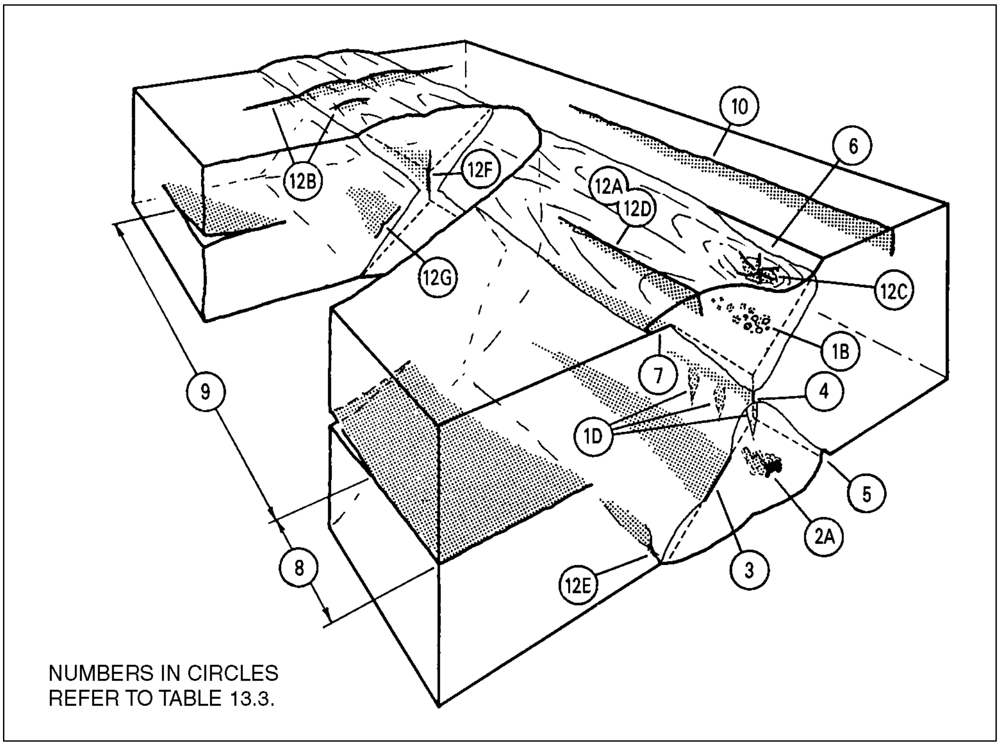


Figure 13.1—Discontinuities in a Double-V-Groove Weld in a Butt Joint

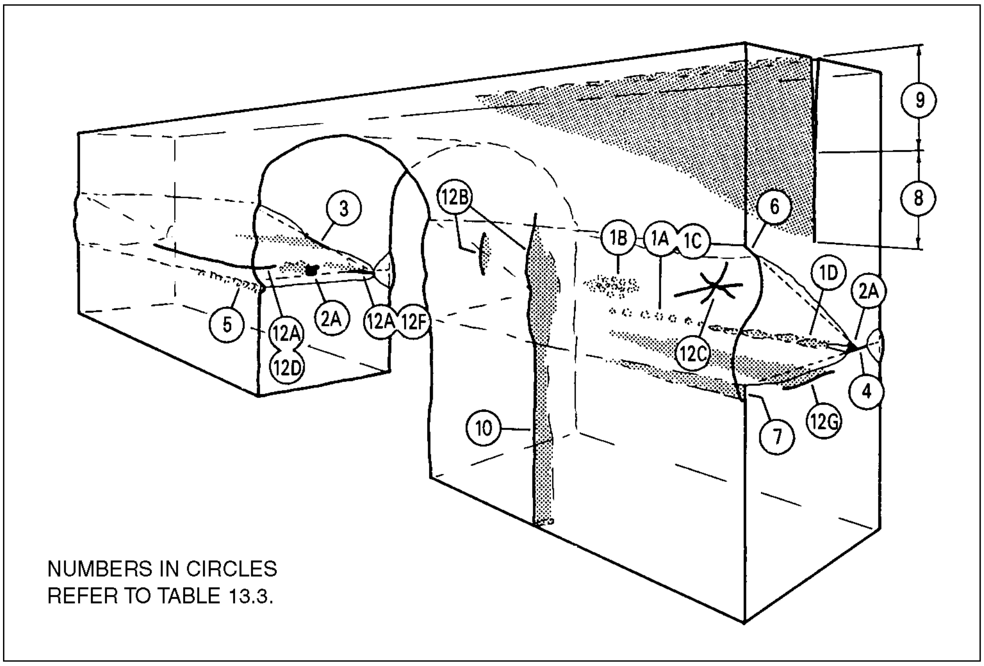


Figure 13.2—Discontinuities in a Single-Bevel-Groove Weld in a Butt Joint

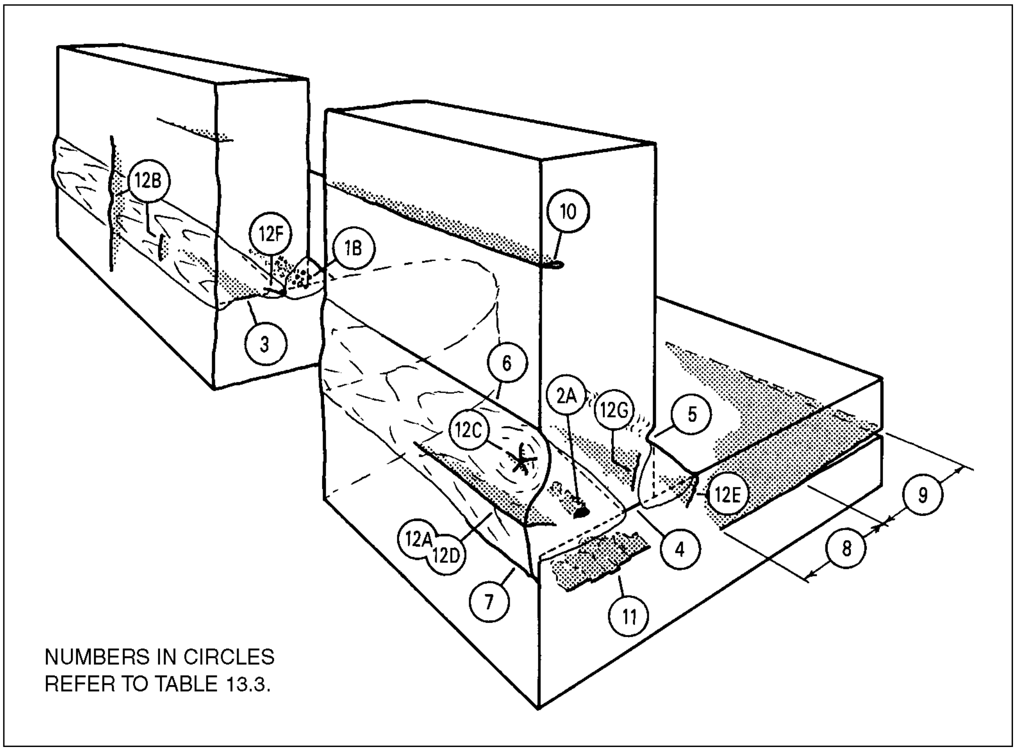


Figure 13.3—Discontinuities in a Single-Bevel-Groove and Fillet Welds in a Corner Joint

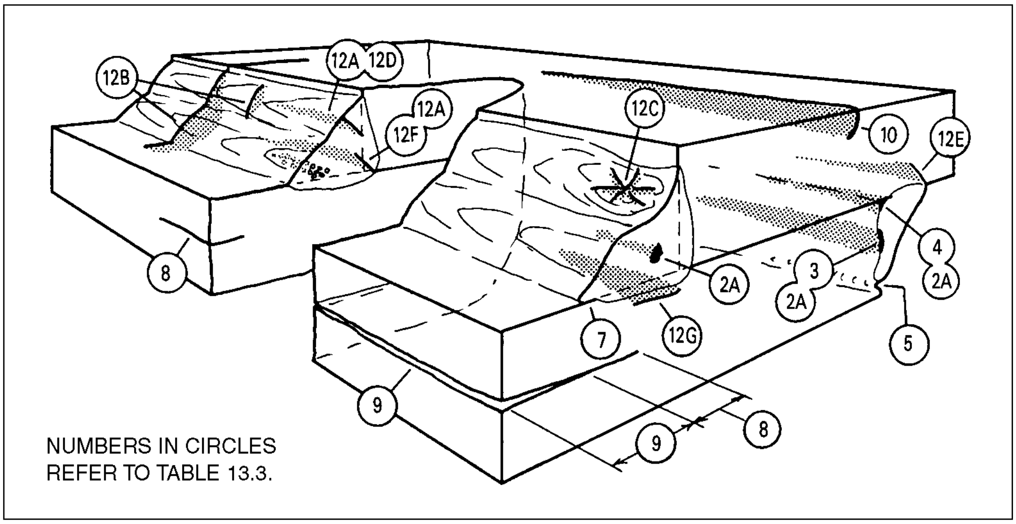


Figure13.4—Discontinuities in a Double Fillet Weld in a Lap Joint

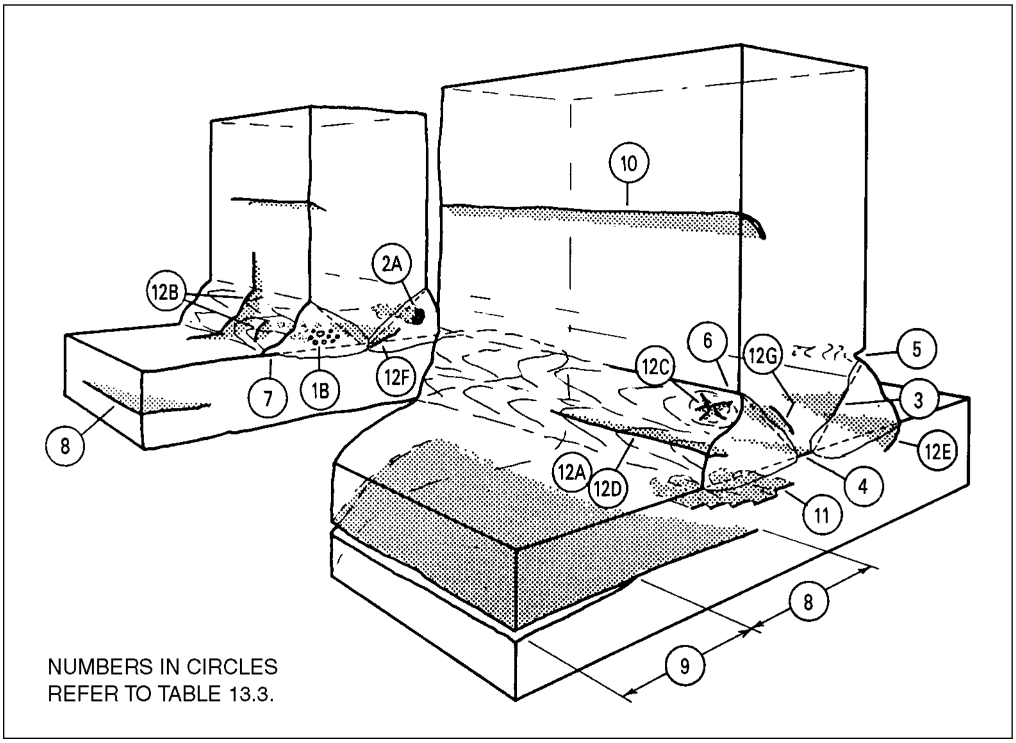


Figure 13.5—Discontinuities in a Double-Bevel Groove Weld in a T-Joint

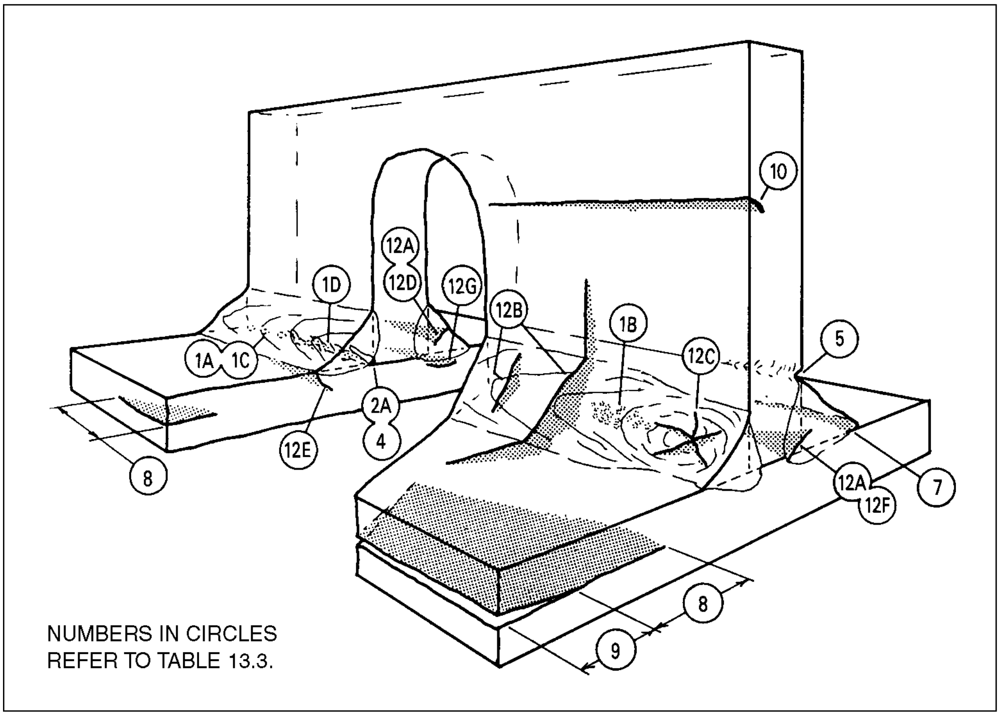


Figure 13.6—Discontinuities in a Single-Pass Double Fillet Weld in a T-Joint

Arc Strike

An arc strike is a discontinuity that results from intentionally or accidentally initiating the arc momentarily on the surface of the base or weld metal away from the intended weld joint. This can be caused by electrodes or electrode holders contacting the workpiece, ground clamps being too close to the weld location, and bare spots in the welding cable, or a combination of these. An arc strike consists of localized remelted metal and heat-affected-zone metal. Arc strikes can initiate failure of the weldment in bending or cyclic loading as these contain hard spots and usually quench cracks. They create a hard and brittle condition in alloy steels and are inadvisable even on mild steel when high tensile stresses or normal cyclic loading may be encountered.

To prevent the occurrence of this discontinuity, the welder or welding operator should avoid striking an arc on base metal that is not intended to be fused into the weld metal. A small volume of base metal may melt momentarily when the arc is initiated. The molten metal may crack from quenching, or a small surface pore may form in the solidified metal. Microscopic examination of the surface and resulting microstructure typically reveals a martensitic structure with a carbon content that is usually higher than expected. These discontinuities may lead to extensive cracking in service. With respect to repair procedures, cracks or blemishes caused by arc strikes should be ground to a smooth contour and reinspected for soundness.

Backing Left On

The discontinuity known as *backing left on* is a procedure-related discontinuity that occurs when the material or device positioned against the back side of the joint to support and shield the molten weld metal is inadvertently allowed to remain in place. This oversight by the welding operator requires correction. It should be noted that when the backing is designed to remain in place, e.g., the interior of a pipe weld, this is not considered a discontinuity.

Burn-Through (Melt-Through)

The term *burn-through* is a nonstandard term for *melt-through,* a procedure-related discontinuity that results from improper welding procedure. An extreme case of this discontinuity is termed *excessive melt-through*. This discontinuity, which is depicted in Figure 13.7, is characterized by visible root reinforcement in a joint welded from one side or a hole in the weld bead. It can be avoided by strictly adhering to the specified procedure and adjusting the welding current and voltage.

Concavity

Concavity, sometimes referred to as *insufficient throat,* is a fillet weld discontinuity in which the maximum distance from the face of a concave fillet weld perpendicular to a line joining the weld toe is insufficient, the amount being specified by the relevant code or standard. Concavity does not constitute a rejectable discontinuity unless the weld throat is undersized. A schematic representation of concavity in a fillet weld is presented in Figure 13.8.

Concavity may result from using an electrode that is too small in diameter, excessive travel speed, low welding current and voltage, poor joint fitup, or excessive gap. Proper welding procedures should be followed to prevent the occurrence of this discontinuity.

Convexity

Convexity is a fillet weld discontinuity in which excessive distance exists between the weld face and a perpendicular line joining the weld toe, the allowable amount of excess being specified by the relevant design documents. When excessive convexity exists in a fillet weld, a notch that may be a crack initiator is created at the weld toe. This discontinuity can also occur in the intermediate beads of multipass welds, which may inhibit the cleaning process and lead to incomplete fusion or inclusions. A schematic illustration of convexity is presented in Figure 13.9.

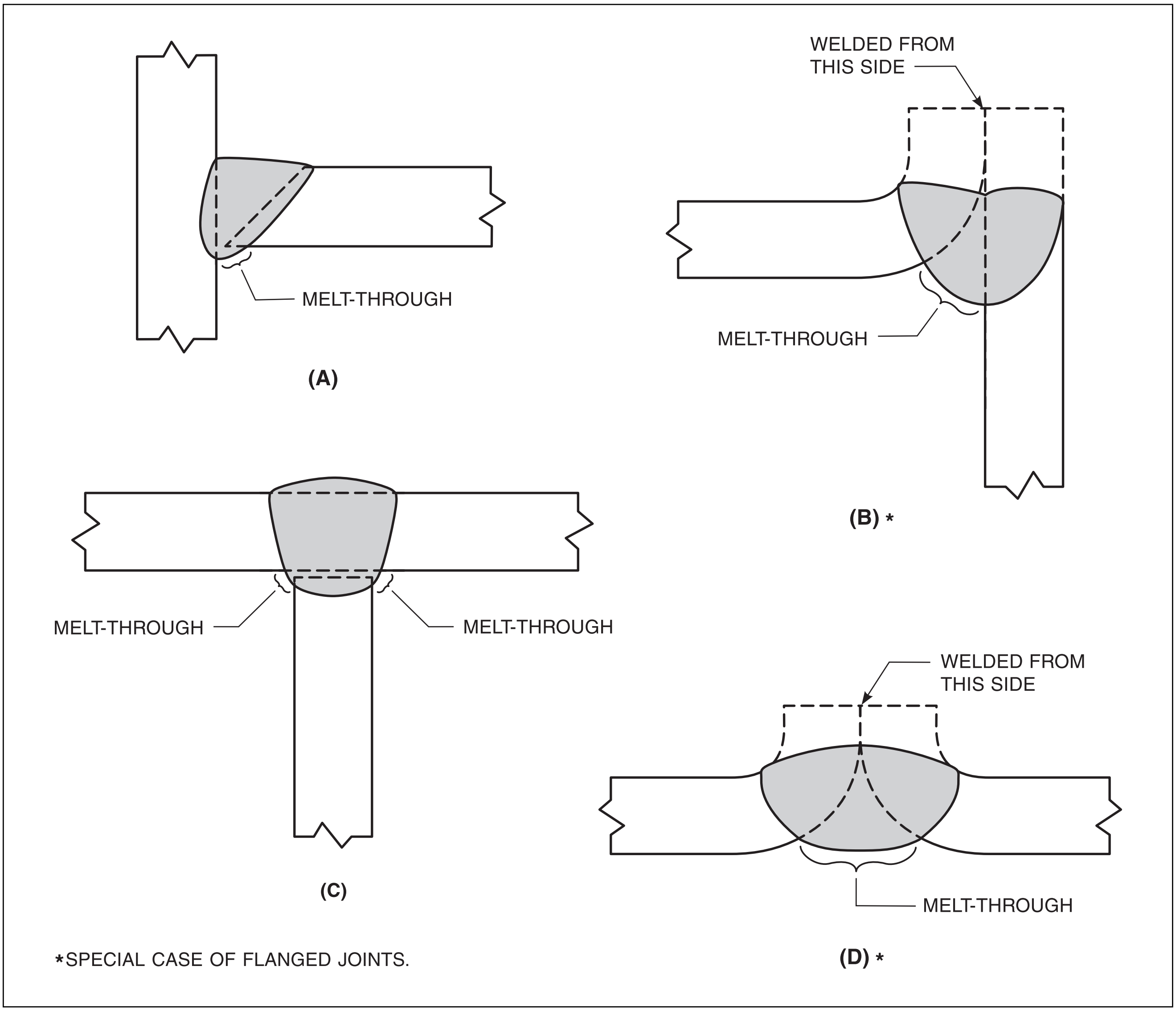
A procedure-related discontinuity, convexity is a consequence of using a low travel speed and high welding current. It may also occur because of surface contamination.

Cracks

Cracks are fracture-type discontinuities. They can be readily identified by their sharp tip and their high ratio of length and width to the displacement of the opening. Because of their tendency to propagate under stress, cracks are considered the most severe form of discontinuity. Cracks are generally the primary cause of catastrophic failure in structures and components. Welders, welding engineers, and designers must therefore strive to avoid this type of discontinuity.

Cracks occur in weld and base metals when localized stresses exceed the ultimate strength of the metal. Cracking is often associated with stress amplification near discontinuities in welds and base metal or near mechanical notches associated with the weldment design. Hydrogen embrittlement may contribute to cold crack formation in steel. Plastic deformation at the crack edges is very limited.

Cracks can be classified as either hot or cold types. Hot cracks develop at elevated temperatures. They com-



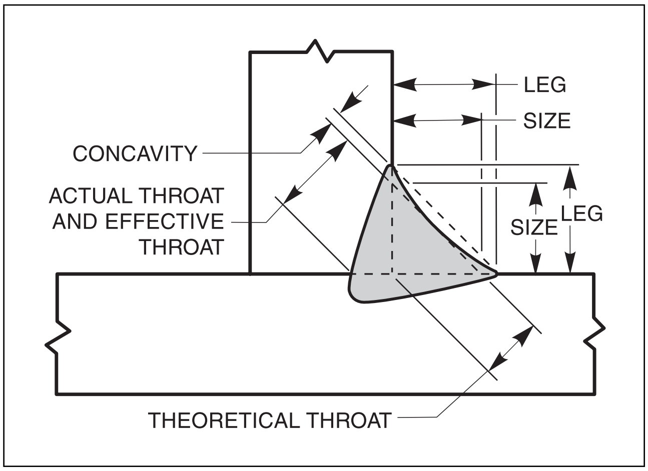
Source: Adapted from American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society, Figure 27.

Figure 13.7—Schematic Representation of Melt-Through

monly form during the solidification of the weld metal. Cold cracks develop after the solidification of a fusion weld as a result of residual stresses. Cold cracks in steel are sometimes referred to as *delayed cracks*. They are often associated with hydrogen embrittlement. Hot cracks propagate between the grains (grain boundary or intergranular), while cold cracks propagate both between the grains and through the grains (transgranular).

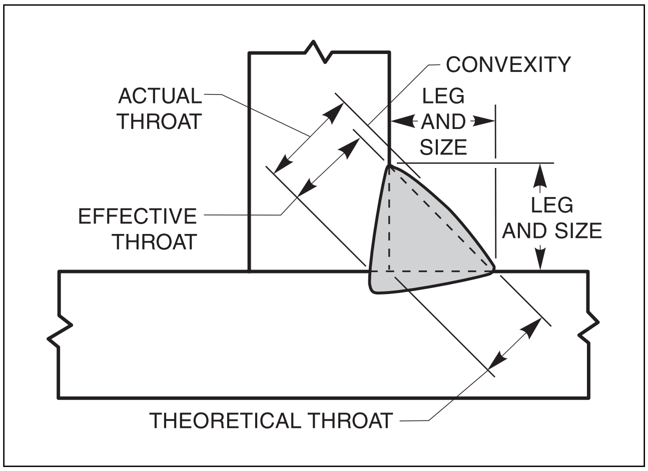
Cracks may be longitudinal or transverse with respect to the weld axis. Longitudinal cracks in the weld metal and the heat-affected zone occur parallel to the axis of the weld. Transverse cracks are found perpendicular to the weld axis.

Cracking in any form is an unacceptable discontinuity, as it is detrimental to performance. Since cracks, by nature, are sharp at their tips or ends, they act as stress concentrators. The stress-concentration effect generated by cracks is greater than that produced by most other discontinuities. Therefore, regardless of their size, cracks are not normally permitted in weldments governed by



Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 34.

Figure 13.8—Concavity in a Fillet Weld



Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 32.

Figure 13.9—Convexity in a Fillet Weld

most fabrication codes. They must be removed regardless of their location, and the excavation must be filled with sound weld metal if the excavation depth exceeds the minimum design thickness for the weldment.

Figure 13.10 illustrates the common types of cracks and presents the crack terminology established by the American Welding Society (AWS). These crack types are described below. A discussion of causes and remedies is presented following these descriptions.

Crater Crack. Crater cracks are usually shallow hot cracks formed by improper termination of a welding arc. Whenever the welding operation is interrupted incorrectly, these cracks may form in the crater. These cracks are often star-shaped and progress only to the edge of the crater. They are sometimes referred to colloquially as *star cracks*. This discontinuity is found most frequently in metals with high coefficients of thermal expansion, such as austenitic stainless steel. Crater cracks may be the starting point for longitudinal weld cracks, particularly when they occur in a crater formed at the end of a single-pass weld. A crater crack is shown in Figure 13.11.

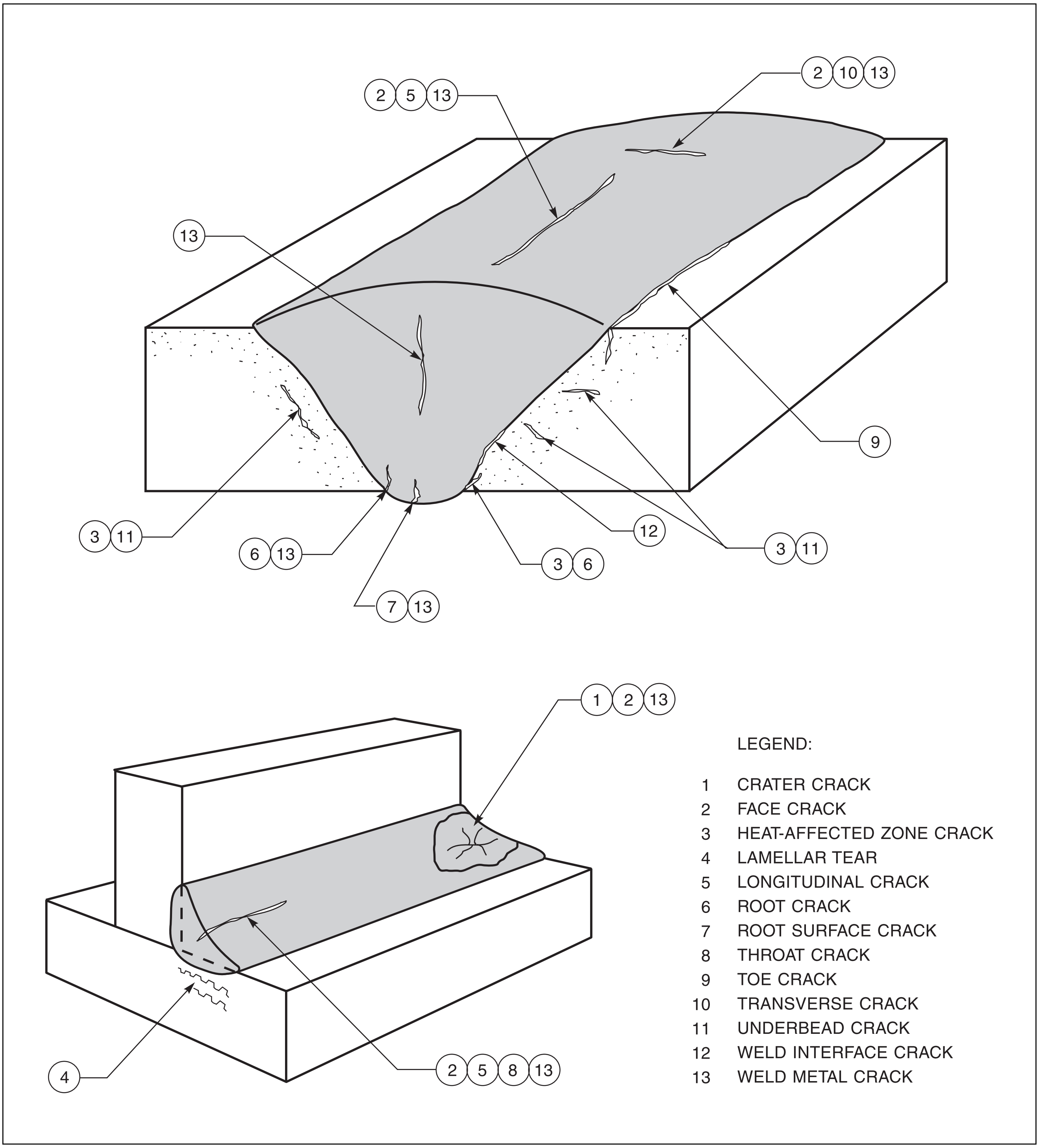
The occurrence of crater cracks can be minimized or prevented by filling craters to a slightly convex shape prior to breaking the welding arc. The use of a welding current delay device when terminating a weld bead can also be effective, especially in mechanized or automated welding operations.

Face Crack. The term *face crack* refers to weld metal cracking. A face crack is a longitudinal crack on the exterior surface of the weld. This discontinuity may result from excessive concavity, insufficient reinforcement, or excessive welding speed. It may also be caused by shrinkage due to rapid cooling. Face cracks can be prevented by strictly adhering to the welding procedure. When they do occur, they should be ground out and rewelded.

Heat-Affected-Zone or Underbead Crack. Heat-affected-zone or underbead cracks are generally cold cracks that form in the heat-affected zone of steel weldments. They are usually short and discontinuous but can extend to form a continuous crack. Underbead cracking usually occurs when three elements are present: (1) hydrogen in solid solution; 2) a microstructure of low ductility, such as martensite; and (3) high residual or applied stress.

These cracks are found at regular intervals under the weld metal in the heat-affected zone of the base metal. They rarely extend to the surface and generally follow the contour of the weld bead. The cracks may be either longitudinal or transverse, depending on the microstructure and the orientation of the residual stress. They cannot be detected by visual inspection and may be difficult to detect by ultrasonic and radiographic examinations.

Longitudinal Crack. Longitudinal cracks are almost always found within the weld metal and are usually confined to the center of the weld. The axis of the crack is parallel to the length of the weld, as shown in Figure 13.12. They may occur in the middle of the weld or at the end of the weld (typical in fillet welds). In the latter case, the cracks may be an extension of another crack



Source: American Welding Society Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, AWS A3.0:2001 Miami: American Welding Society, Figure 33.

Figure 13.10—Crack Types

Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 25.

Figure 13.11—Crater Crack

Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 22.

Figure 13.12—Longitudinal Crack in Combination with Linear Porosity

that initiated in the root bead and continued to propagate through the entire thickness of the weld.

One cause of longitudinal cracking is a high degree of restraint in the joint, which can initiate a crack around a discontinuity such as porosity or trapped slag in the weld. Another typical cause of longitudinal cracking is shrinkage stress in heavy sections or in joints between heavy and thin joint members. This may occur in high-speed welding such as is common in submerged arc welding, gas metal arc welding, and flux cored arc welding and in welds fabricated with automated equipment. Longitudinal cracks in small welds between heavy sections are often the result of rapid cooling rates and high restraint.

Root Crack. Root cracks run longitudinally along the weld root or in the weld surface. They can be either hot or cold cracks. These discontinuities may be either procedure-related or metallurgical in nature due to the characteristics of the material being welded. They can result from incomplete penetration or pretreatment, excessive travel speed, or too large a gap (spacing). Root cracks can also occur because of surface contamination or the incorrect use of a consumable insert. The specified welding procedure should be carefully followed to prevent their occurrence.

Root Surface Crack. Root surface cracks are fracture-type discontinuities that are located on the exposed surface of the weld opposite the side from which welding was performed. These discontinuities can be procedure-related or metallurgical in nature. They can be prevented primarily by adhering strictly to the welding procedure.

Throat Crack. Throat cracks are cracks that run longitudinally in the face of the weld and extend toward the root of the weld. They are generally, but not always, hot cracks. A typical throat crack is presented in Figure 13.13. As throat cracks are a form of longitudinal cracking, the reader is encouraged to refer to the section titled "Longitudinal Cracking," presented above.

Toe Crack. Toe cracks are generally cold cracks that initiate approximately parallel to the base material surface and then propagate from the toe of the weld where residual stresses are higher. These cracks are generally the result of thermal shrinkage strains acting on a weld heat-affected zone that has been embrittled. Toe cracks sometimes occur when the base metal cannot accommodate the shrinkage strains that are imposed by welding. A typical toe crack is shown in Figure 13.14.

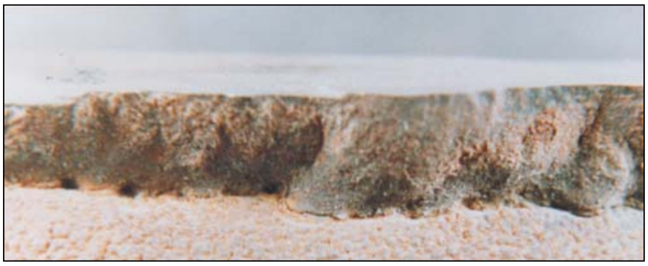
Toe cracks also initiate in fillet weld joints subjected to fatigue loading, such as occurs in small-diameter piping socket joints. Fatigue loading on these welds may cause toe cracks that propagate through the pipe from the weld toe, where the stresses are concentrated.

Transverse Crack. A discontinuity of the weld metal, transverse cracks run nearly perpendicular to the axis of the weld. They may be limited in size and completely within the weld metal, or they may propagate from the weld metal into the adjacent heat-affected zone and the base metal. Transverse cracks are generally the result of longitudinal shrinkage strains acting on weld metal of low ductility. Transverse cracks in steel weld metals are typically related to hydrogen embrittlement. This type of crack, pictured in Figure 13.15, is common in joints that have a high degree of restraint.

Weld Metal Crack. The generic term *weld metal crack* is used to refer to cracks that occur in the weld metal.

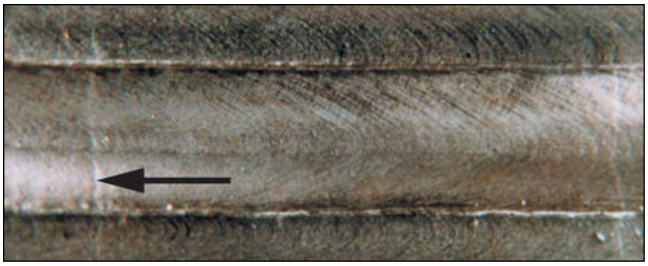
Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 24.

Figure 13.13—Throat Crack



Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 28.

Figure 13.14—Toe Crack



Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 23.

Figure 13.15—Transverse Crack

Causes of Cracking and Remedies. Cracking in welded joints results from localized stresses that exceed the ultimate strength of the metal. When cracks occur during or as a result of welding, they do not normally exhibit evidence of deformation. Weld metal or base metal that has considerable ductility under uniaxial stress may fail without appreciable deformation when subjected to biaxial or triaxial stresses. Shrinkage occurs in all welds, and if a joint or any portion of it (such as the heat-affected zone) cannot accommodate the shrinkage stresses by plastic deformation, then high stresses develop. These stresses can and do cause cracking.

An unfused area at the root of a weld may result in cracks without appreciable deformation if this area is subjected to tensile or bending stresses. When welding two plates together, the root of the weld is subjected to tensile stress as successive layers are deposited. Incomplete fusion in the root promotes cracking.

The chemical compositions of the base metal and the weld metal affect crack susceptibility. After a welded joint has cooled, cracking is more likely to occur if the weld metal or heat-affected zone is either hard or brittle. A ductile metal, by localized yielding, may withstand stress concentrations that might cause a hard or brittle metal to fail. Cracking in the weld metal, the heat-affected zone, and the base metal is discussed in further detail below.

Weld Metal Cracking. Transverse and longitudinal cracks as well as crater cracks occur in the weld metal in welds produced by fusion welding. The ability of the weld metal to remain intact under a stress system imposed during a welding operation is a function of the composition and structure of the weld metal. In multiple-layer welds, cracking is most likely to occur in the first layer (root bead) of weld metal. Unless such cracks are repaired, they may propagate through subsequent layers as the weld is completed. Resistance to cracking in the weld metal can be improved with the implementation of one or more of the following procedures:

1. Modifying electrode manipulation or electrical conditions to improve the weld face contour or the composition of the weld metal,
2. Selecting an alternate filler metal to develop a more ductile weld metal,
3. Increasing the thickness of each weld pass by decreasing the welding speed and providing more weld metal to resist the stresses,
4. Using preheat to reduce thermal stresses,
5. Using a low-hydrogen welding procedure,
6. Sequencing welds to balance shrinkage stresses, and
7. Avoiding rapid cooling conditions.

Heat-Affected Zone Cracking. Cracks in the heat-affected zone may be longitudinal or transverse in nature. They are typically associated with hardenable base metals. High hardness and low ductility in the heat-affected zone result from the metallurgical response to the weld thermal cycles.[15] These two condi-

15. The metallurgical response to weld thermal cycles is discussed in Chapter 4 of this volume.

tions are among the principal factors that contribute to crack susceptibility.

In ferritic steels, as the carbon content and cooling rates increase, the maximum attainable hardness increases while the ductility decreases. The rate of cooling depends upon a number of physical factors, including the following:

1. Peak temperature produced in the heat-affected zone,
2. Initial temperature of the base metal (preheat),
3. Thickness and thermal conductivity of the base metal,
4. Heat input per unit time at a given section of the weld, and
5. Ambient temperature.

The hardness of the heat-affected zone is related to the hardenability of the base metal, which is dependent, in turn, on the chemical composition of the base metal. Carbon has the strongest effect on the hardenability of steel. In addition, it increases the hardness of the transformation products. Nickel, manganese, chromium, and molybdenum also contribute to the hardenability of steel. However, unlike carbon, these elements only moderately increase the hardness of the base metal.

High-alloy steels include the austenitic, ferritic, and martensitic stainless steels. Although the martensitic stainless steels behave similarly to medium-carbon and low-alloy steels, they are more susceptible to cracking. Austenitic and ferritic stainless steels do not undergo a phase transformation that hardens the heat-affected zone. The ductility of the heat-affected zone in ferritic stainless steels may be adversely affected by welding.

The metallurgical characteristics of the base metal affect the crack susceptibility of the heat-affected zone. Small changes in the chemical composition of the base metal and the filler metal (hydrogen content) as well as added joint restraint can appreciably increase cracking. Significant differences are encountered in crack susceptibility among several heats of the same grade of low-alloy steel.

Base Metal Cracking. When welding many varieties of steels, the primary problem encountered with respect to the cracking of the base metal is caused by soluble hydrogen.[16] Known by a variety of terms, including *underbead cracking*, *cold cracking*, and *delayed cracking*, hydrogen-induced cracking typically occurs at temperatures below 200°F (100°C) immediately upon cooling or after a period of several hours. The time delay depends on the type of steel, the magnitude of the welding stresses, and the hydrogen content of the weld and heat-affected zones. In any case, it is caused by diffusible hydrogen trapped in the weld metal or the heat-affected zone. The weld metal may crack, but this seldom occurs when the yield strength is below 90 kips per square inch (ksi) [620 megapascal (MPa)].

The diffusion of hydrogen into the heat-affected zone from the weld metal during welding contributes to cracking in the base metal. The microstructures of the weld metal, the heat-affected zone, and the base metal are also contributing factors.

Hydrogen-induced cracking can be prevented by using a low-hydrogen welding process. A combination of welding and thermal treatments that promotes the escape of hydrogen by diffusion may also produce a microstructure that is more resistant to hydrogen-induced cracking. Another preventive measure involves the use of welding procedures that result in low welding stresses.

The causes and remedies of cracking in the weld metal, the base metal, and the heat-affected zone are summarized in Table 13.4.

Excessive Weld Reinforcement

Excessive weld reinforcement exists in a groove weld when the weld metal is in excess of the quantity required to fill the joint. This discontinuity may be located at the root or face of a groove weld. It is highly undesirable when it concentrates stresses at the toe of the weld. Excessive weld reinforcement may be caused by improper welding technique or overwelding.

Inclusions

Inclusions are solid materials trapped in the weld metal or at the interfaces of the weld metal. The foreign materials that are often entrapped include tungsten, flux, oxide, and slag. Inclusions may be encountered in welds produced with most arc welding processes but are most common in the flux shielded processes, such as shielded metal arc welding, flux cored arc welding, and submerged arc welding.

The common causes of inclusions and suggested remedies are shown in Table 13.5.

Tungsten Inclusions. Tungsten inclusions are particles of the tungsten electrode trapped in weld metal deposited with the gas tungsten arc or plasma arc welding processes. These inclusions may be trapped in a weld if the tungsten electrode is dipped into the molten weld metal, the tungsten electrode touches the base metal, or if the welding current is too high and causes the melting and transfer of tungsten droplets into the molten weld metal.

Tungsten inclusions appear as light areas on radiographs because tungsten is denser than the surrounding

16. Hydrogen-induced cracking is discussed in detail in Chapter 4 of this volume.

Table 13.4
Cracking—Common Causes and Remedies

Causes	Remedies
Weld-Metal Cracking	
Highly rigid joint	Preheat; relieve residual stresses mechanically; minimize shrinkage stresses using backstep or block welding sequence
Excessive dilution	Change welding current and travel speed; weld with covered electrode negative; butter the joint faces prior to welding
Defective electrodes	Change to new electrode; bake electrodes to remove moisture
Poor fitup	Reduce root opening; build up the edges with weld metal
Small weld bead	Increase electrode size; raise welding current; reduce travel speed
High-sulfur base metal	Use filler metal low in sulfur
Angular distortion	Change to balanced welding on both sides of joint
Crater cracking	Fill the crater before extinguishing the arc; use a welding current decay device when terminating the weld bead
Heat-Affected-Zone and Base Metal Cracking	
Hydrogen in welding atmosphere	Use a low-hydrogen welding process; preheat and hold for 2 hours after welding or postweld heat treat immediately
Hot cracking	Use low heat input; deposit thin layers; change base metal
Underbead cracking	Preheat; reduce cooling rate and stress
Low ductility	Use preheat; anneal the base metal
High residual stresses	Redesign the weldment; change welding sequence; apply intermediate stress-relief heat treatment
High hardenability	Preheat; increase heat input; heat treat without cooling to room temperature

Table 13.5
Inclusions—Common Causes and Remedies

Cause	Remedy
Failure to remove slag	Clean the surface and the previous weld bead
Entrapment of refractory oxides	Power wire brush the previous weld bead
Tungsten in the weld metal	Avoid contact between the electrode and the work; use a larger electrode
Improper joint design	Increase groove angle of joint
Oxide inclusions	Provide proper gas shielding
Slag flooding ahead of the welding arc	Reposition work to prevent loss of slag control or change electrode manipulation technique
Poor electrode manipulative technique	Change electrode or flux to improve slag control
Entrapped pieces of electrode covering	Use undamaged electrodes

metal and absorbs larger amounts of X-rays or gamma radiation. Almost all other weld discontinuities are indicated by dark areas on radiographs.

Flux Inclusions. As the term suggests, flux inclusions result when flux becomes entrapped in the weld prior to solidification. In flux cored arc welding, this discontinuity may arise from the use of an improper electrode, whereas in submerged arc welding, it may result from the use of the incorrect welding current.

Flux inclusions may occur if pieces of the electrode covering break off and become trapped in the weld puddle. They may also occur in flux cored arc welding or in gas metal arc welding and submerged arc welding (cored wires only) if flux or alloying materials fail to melt and become trapped in the weld.

Oxide Inclusions. Oxide inclusions, surface oxides trapped in the weld, may result from the dissociation of the electrode coating. These can become isolated inclusions in multipass welds. They are easily found and removed, since they initially appear on the surface of weld beads.

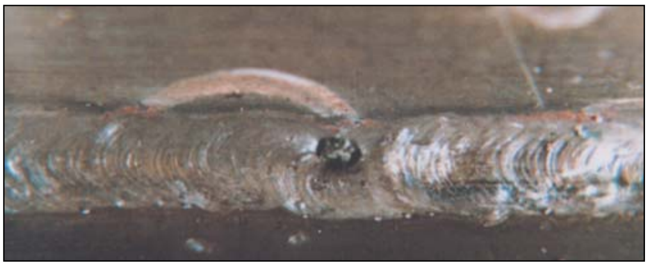
Slag Inclusions. Slag inclusions, like that depicted in Figure 13.16, typically result from faulty welding techniques, improper access to the joint for welding, or both. With proper welding techniques, molten slag floats to the surface of the molten weld metal. Sharp notches in joint boundaries or between weld passes promote slag entrapment in the weld metal.

Entrapped slag discontinuities typically occur only with the flux shielded welding processes—shielded metal arc, flux cored arc, submerged arc, and electroslag welding. Entrapped slag is a reaction product of the flux and the molten weld metal. Oxides, nitrides, and other impurities may dissolve in the slag to refine the weld metal. As slag is less dense than the weld metal, it normally floats to the surface.

During welding, slag is formed and may be forced below the surface of the molten weld metal by the stirring action of the arc. Slag may also flow ahead of the arc, and metal may be deposited over it. The latter is especially true when multipass welds are made without proper interpass cleaning.

A number of factors may prevent the release of slag and result in its entrapment in the weld metal. These factors include the following:

1. High-viscosity weld metal,
2. Rapid solidification,
3. Insufficient welding heat,
4. Improper manipulation of the electrode, and
5. Undercut on previous passes.



Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 30.

Figure 13.16—Slag Inclusion

Geometric factors such as poor bead profile, sharp undercuts, or improper groove geometry promote the entrapment of slag by providing places where it can accumulate beneath the weld bead. In making a root pass, if the electrode is too large and the arc impinges on the groove faces instead of on the root faces, the slag may roll down into the root opening and be trapped under the weld metal. Some of the factors that contribute to slag entrapment can be controlled by welding technique.

The influence of slag inclusions on weld behavior is similar to that of porosity. The effect of slag inclusions on static tensile properties is significant principally to the extent it influences the cross-sectional area available to support the load. The toughness of the weld metal seems to be unaffected by isolated slag with volumes of 4% or less of the weld zone. In weld metals of less than 75 ksi (517 MPa) tensile strength, ductility is generally unaffected. As the tensile strength increases, however, ductility drops in proportion to the amount of slag present.

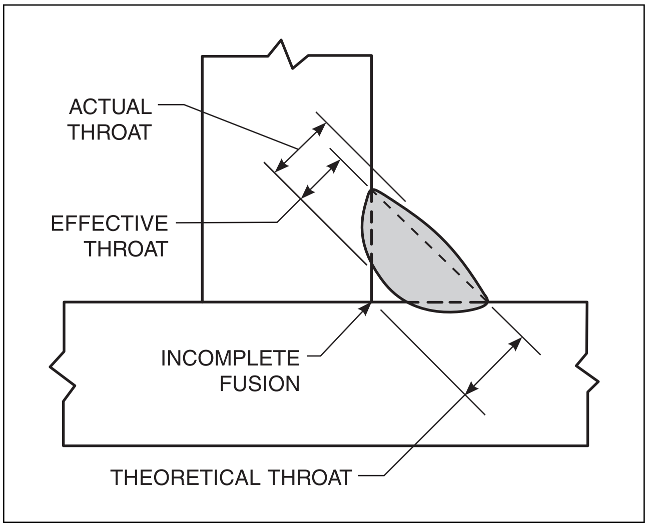
Slag inclusions often have "tails" that act as stress raisers. Therefore, slag can influence the fatigue behavior of welds, particularly when the weld reinforcement is removed and the weld is not postweld heat-treated. As with porosity, slag at or very near to the weld surface (face or root) influences fatigue behavior to a considerably greater extent than similarly constituted slag buried within the weld metal. Slag, together with hydrogen dissolved in the weld metal, influences fatigue strength by reducing the critical slag particle size necessary for the initiation of a fatigue crack.

Incomplete Fusion

Incomplete fusion, illustrated schematically in Figure 13.17, is a discontinuity in which fusion failed to occur between the base metal and the weld metal or the adjoining weld beads. Failure to obtain fusion may occur at any point in a groove or fillet weld, including the root. A photograph of incomplete fusion is presented in Figure 13.18.

Intermittent incomplete fusion affects weld joint integrity in much the same manner as porosity and inclusions. The degree to which intermittent incomplete fusion can be tolerated in a welded joint for various types of loading is similar to the limits for porosity and slag inclusions. Continuous incomplete fusion has the same effect as incomplete joint penetration, which is discussed in the next section.

Incomplete fusion typically occurs as a result of improper welding techniques for a given joint geometry and welding process, improper preparation of the materials for welding, or inappropriate joint design. It may be caused by failure to melt the base metal or the previously deposited weld metal, or both. The welding con-



Source: American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions*, AWS A3.0:2001, Figure 25(C).

Figure 13.17—Schematic Illustration of Incomplete Fusion in a Fillet Weld

Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 6.

Figure 13.18—Incomplete Fusion

ditions that contribute to incomplete fusion include insufficient welding current, improper heat input, inappropriate handling of the electrode, and limited access to all faces of the weld joint that should be fused during welding. Insufficient preweld cleaning may contribute to incomplete fusion, even if the welding conditions and technique are adequate. Preweld cleaning is critical in certain metals.

Although this discontinuity is generally related to weld technique, the presence of oxides or other foreign materials, such as slag, on the surfaces of the metals may also promote the occurrence of incomplete fusion. In some cases, unsuitable combinations of joint design and welding process may lead to incomplete fusion.

The causes of incomplete fusion and suggested remedies are summarized in Table 13.6.

Incomplete Joint Penetration

Incomplete joint penetration, generally associated with groove welds, is a root condition in which the weld metal does not extend through the joint thickness. Complete joint penetration is not required in all welded joints as some joints are designed with partial joint penetration welds. However, such welds can have incomplete joint penetration when the effective throat of the weld is less than that specified in the welding symbol. The occurrence of incomplete joint penetration in welds is a function of groove geometry as well as welding procedure. Pipe welds, in particular, are prone to incomplete joint penetration, as the inside of the joint is normally inaccessible.

Some welding processes have great penetrating ability, a characteristic that is often used to advantage. However, the process must be matched to the joint preparation to avoid incomplete fusion. Many welding procedures for double-groove welds require backgouging of the root of the first weld to expose sound metal prior to depositing the first pass on the second side. This procedure is used to ensure that there are no areas of incomplete joint penetration.

Table 13.6
Incomplete Fusion—Common Causes and Remedies

Causes	Remedies
Insufficient heat input, wrong type or size of electrode, improper joint design, or inadequate gas shielding	Follow correct welding procedure specification
Incorrect electrode position	Maintain proper electrode position
Weld metal running ahead of the arc	Reposition work, lower current, or increase weld travel speed
Trapped oxides or slag on weld groove or weld face	Clean weld surface prior to welding

Shown in Figure 13.19, incomplete joint penetration may result from insufficient welding heat, excessively rapid travel speed, improper joint design (too much metal for the welding arc to penetrate), incorrect bevel angle, or poor control of the welding arc. This type of discontinuity is undesirable in any groove weld subjected to cyclic tension loading in service. The discontinuity can initiate a crack that may propagate and result in catastrophic failure. In welds deposited from one side of the joint, those with incomplete joint penetration may be loaded in bending at the root, and the concentration of stress may cause failure without appreciable deformation. If the joint is welded from both sides and incomplete joint penetration is present at the neutral axis, the bending stresses are lower, but they are concentrated at the ends of the discontinuity.

Furthermore, buried incomplete joint penetration is more difficult to detect than a discontinuity at the surface. As visual examination usually fails to reveal this discontinuity, other nondestructive examination methods such as ultrasonic examination must be used. The causes and remedies of incomplete joint penetration are summarized in Table 13.7.

The repair of incomplete joint penetration depends on the requirements of the joint design. When the weld is required to extend completely through the joint, repair can be made by backgouging to sound metal from the back side and applying a second-side weld. When only partial joint penetration is required or the back side of the weld is inaccessible, the weld must be removed. The joint should then be rewelded using a modified welding procedure that provides the required weld size.

Overlap

Overlap exists when unfused weld metal protrudes beyond the weld toe or root. This surface discontinuity forms a severe mechanical notch parallel to the weld axis, which usually renders the weld unacceptable. A photograph illustrating overlap is presented in Figure 13.20.

Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 12.

Figure 13.19—Incomplete Joint Penetration

Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 18.

Figure 13.20—Overlap

Table 13.7
Incomplete Joint Penetration—Common Causes and Remedies

Causes	Remedies
Excessively thick root face or insufficient root opening	Use proper joint geometry
Insufficient heat input	Follow welding procedure
Slag flooding ahead of welding arc	Adjust electrode or work position
Electrode diameter too large	Use small electrodes in root or increase root opening
Misalignment of second side weld	Improve visibility or backgouge
Failure to backgouge when specified	Backgouge to sound metal if required in welding procedure specification
Bridging of root opening	Use wider root opening or smaller electrode in root pass

Overlap is usually caused by incorrect welding procedures, inappropriate selection of welding materials, insufficient travel speed, or improper preparation of the base metal prior to welding. If tightly adhering oxides on the base metal interfere with fusion, overlap may result along the toe, face, or root of the weld.

Oxide Film

Oxide film is a process and procedure-related discontinuity that results from improper weld preparation or the use of improper shielding gas or flux.

Porosity

Porosity is a cavity-like discontinuity that forms when gas is entrapped in solidifying weld metal or in a thermal spray deposit. The discontinuity is generally spherical, but it may be elongated. This type of weld discontinuity occurs on the surface or in the subsurface of the weld. The various types of porosity are described below followed by a discussion of the causes of porosity.

Scattered Porosity. Scattered porosity, illustrated in Figure 13.21, may be distributed throughout single-pass welds, contained in one pass of a multipass weld, or spread throughout several passes of multiple pass welds. Whenever scattered porosity is encountered, the cause is generally faulty welding technique, contaminated or incorrect shielding gases, contaminants on the surface of the workpiece, or defective materials.

Cluster Porosity. Cluster porosity manifests itself as a localized grouping of pores with a random geometric distribution. It frequently results from improper initiation or termination of the welding arc. The same conditions that cause arc blow can also contribute to the formation of cluster porosity.

Piping Porosity. The term *piping porosity* denotes a form of porosity that has a length greater than its width and lies approximately perpendicular to the weld face. In fillet welds, elongated porosity normally extends from the root of the weld toward the face. When one or two pores are seen in the surface of the weld, it is likely that many subsurface piping pores are interspersed among the exposed pores. Much of the piping porosity found in welds does not extend to the surface. In electroslag welds, piping porosity is generally characterized by relatively long pores. This discontinuity is typically caused by rapid solidification.

Aligned Porosity. Aligned porosity, sometimes referred to as *linear porosity,* consists of a localized array of spherical or elongated pores oriented in a line. This porosity may be aligned along a weld interface, at the root of a weld, or at a boundary between weld beads. It is caused by gas evolution from contaminants at the location where the discontinuity has formed.

Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 2.

Figure 13.21—Scattered Porosity

Elongated Porosity. Elongated porosity resembles piping porosity in that this discontinuity has a length greater than its width. However, in contrast to piping porosity, this discontinuity lies approximately parallel to the weld axis.

Causes. The typical causes of porosity in weld metal are related to the welding process and the welding procedure, and in some instances, to the type and chemistry of the base metal. The welding process, welding procedure, and type of base metal (including the manufacturing method) directly affect the quantities and types of gases that are present in the molten weld pool. The welding process and welding procedure control the solidification rate, which in turn affects the amount of weld metal porosity. Proper welding procedures for a given combination of welding process and base metal should produce welds that are essentially free of porosity.

Dissolved gases are usually present in molten weld metal. Porosity is formed as the weld metal solidifies if the dissolved gases are present in amounts greater than their solid solubility limits. The gases that may be present in the molten weld pool include hydrogen, oxygen, nitrogen, carbon monoxide, carbon dioxide, water vapor, hydrogen sulfide, argon, and helium. Of these, only hydrogen, oxygen, and nitrogen are soluble to any significant extent in a molten weld pool, and the solubility of these gases in solidified metal is significantly less than in liquid metal.

Hydrogen is the major cause of porosity in the welding of metals. It may enter the molten weld pool from many sources. For example, it may be present in the gas atmosphere surrounding the arc zone or in hydrogen-forming constituents, such as cellulose in the flux or electrode covering. Hydrogen may also be introduced into the molten weld pool by the dissociation of water. Moisture may be present in fluxes, electrode coverings, ambient atmosphere, or on the base metal surfaces. Residual lubricant from wire drawing can remain on filler wire surfaces and can become a significant contributor to weld metal hydrogen content, particularly with small diameter electrodes. Hydrogen dissolved in the base metal itself or in surface oxides may remain in the weld metal. Filler metals may also contain dissolved hydrogen. Sulfur or selenium in the base metal may combine with hydrogen to form other gases.

Nitrogen may cause porosity in steel and nickel alloy welds. This gas may enter the molten weld pool from the atmosphere or from contaminated shielding gas. It may also be present in the base metal or filler metal in the form of dissolved nitrogen or nitrides.

Oxygen dissolved in the molten weld metal may also cause porosity. When present in molten steel, oxygen reacts with carbon to form carbon monoxide or carbon dioxide. Oxygen may enter the molten weld pool as oxides on filler wire or base metal, or both, in the form of compounds in a flux or an electrode covering, and from the atmosphere. Insufficient amounts of deoxidizers in steel base metals, filler metals, flux, or electrode coverings may result in incomplete deoxidation of the molten weld pool.

Porosity has been evaluated extensively. Tests have been conducted to determine its effects on both the static and dynamic behaviors of welded joints using virtually all types of base metals. It has been found that porosity in amounts less than 3% by volume has an insignificant effect on static tensile or yield strength. This level is generally higher than that permitted by industry fabrication standards. The effect of porosity on ductility is slightly more pronounced. The higher the yield strength of the metal, the greater is the adverse effect of porosity on ductility.

The gas or other contaminant causing porosity may influence the properties of the weld metal by dissolving in it. The gas in the pores or cavities may also influence the metal surrounding the pore. The pore then acts as a crack initiator when the weldment is loaded in service. Though hydrogen has this effect in steel, other gases such as small amounts of oxygen and nitrogen may not.

The influence of porosity on the dynamic toughness of weld metal is less certain. The designer should investigate the effects of porosity on welds subjected to the expected type of loading before specifying acceptable porosity limits for a weldment. The effect of porosity in ferrous metal welds is mitigated to a great extent by a postweld treatment.

In face-centered-cubic alloys such as aluminum (Al), copper (Cu), and nickel (Ni), the influence of porosity is minimal. At high temperatures (i.e., the creep range), the reduction in properties is in proportion to the loss in cross-sectional area.

The most significant studies of porosity have addressed its effect on the fatigue properties of fusion-welded butt joints with and without weld reinforcement. The effect of any amount of porosity on the fatigue strength of reinforced welds was shown to be overshadowed by stress concentrations on the surfaces. However, when the weld reinforcement was removed, exposed porosity contributed to failure by fatigue.

For fillet welds, the stress concentration effects of the weld toe and the start and stop locations are great, and they override all porosity considerations. Internal porosity in fillet welds does not appear to affect service performance. However, the effect of surface porosity in butt and fillet welds is slightly different. Surface porosity is considered more detrimental than buried or internal porosity, but certainly no worse than a crack. Surface porosity may reduce the effective throat of the weld below the minimum needed to support the desired load. Surface porosity often indicates that the welding process is not being performed in accordance with procedure requirements.

The common causes of porosity and suggested methods for its correction are summarized in Table 13.8.

Spatter

In fusion welding, molten metal particles expelled from the arc that do not form part of the weld are referred to as *spatter*. Shown in Figure 13.22, spatter is not necessarily a defect, but it is a concern when finish requirements must be met, typically when painting, coatings, or nondestructive examination is required. Nonetheless, the occurrence of this phenomenon most likely indicates the use of an improper welding technique or other associated process problems.

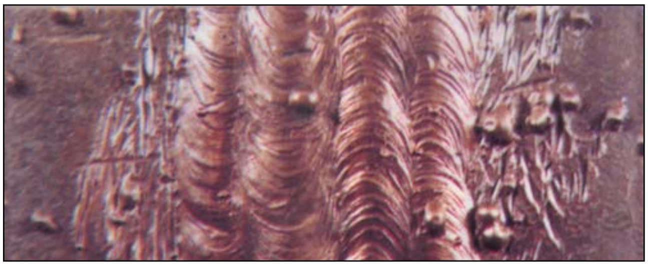
Surface Irregularities

Sharp, excessive surface ripples, excessive spatter, craters, protrusions (such as an overfilled crater), arc strikes, and surface pores are surface irregularities that may be observed on welds. These are some of the typical surface irregularities that may affect the quality of the weldment and its suitability for use. Several of these items are discussed elsewhere in this chapter.

The welder or welding operator is often directly responsible for these discontinuities since they result from incorrect welding technique or improper machine settings. Although the joint may be adequate for its intended service, poor quality should not be accepted as it indicates that the proper procedures are not being followed. Failure to modify the procedures can lead to more serious quality problems. In some cases, faulty or wet electrodes

Table 13.8
Porosity—Common Causes and Remedies

Causes	Remedies
Excessive hydrogen, nitrogen, or oxygen in the welding atmosphere	Use low-hydrogen welding process and filler metals high in deoxidizers; increase shielding gas flow
High solidification rate	Use preheat or increase heat input
Dirty base metal	Clean joint faces and adjacent surfaces
Dirty filler wire	Use specially cleaned and packaged filler wire and store it in clean area
Improper arc length, welding current, or electrode manipulation	Change welding conditions and techniques
Volatilization of zinc from brass	Use copper-silicon filler metal; reduce heat input
Galvanized steel	Remove zinc before welding; use E6010 electrodes and manipulate the arc heat to volatilize the zinc ahead of the molten weld pool
Excessive moisture in the electrode covering or on joint surfaces	Use recommended procedures for baking and storing electrodes; preheat the base metal



Source: American Welding Society (AWS) Committee on Methods of Inspection, 2000, *Guide for the Visual Examination of Welds*, AWS B1.11:2000, Miami: American Welding Society, Figure 35.

Figure 13.22—Spatter

and unsuitable base metal chemistry may cause discontinuities and unsatisfactory weld appearance.

Magnetic disturbances, poor welding technique, and improper electrical conditions can account for certain surface irregularities. Such conditions might be caused by a lack of welding experience, inaccessibility to the weld joint, or other factors peculiar to a specific job. As a rule, surface appearance reflects the ability and experience of the welder, and the presence of gross surface irregularities may be deleterious. Welds with uniform surfaces are desirable for structural as well as cosmetic reasons.

Gross irregularities in the weld bead are discontinuities, as they constitute an abrupt change of section. Considering that such changes of section are potential sources of high stress concentration, they should be carefully evaluated with respect to service requirements.

Various other surface irregularities are not classified as weld discontinuities; nonetheless, they involve poor surface appearance, indicating that the specified welding procedure was not followed or that a satisfactory welding technique was not used. These include varying widths of weld surface layers, depressions, variations in weld height or reinforcement, and nonuniform weld ripples. Although surface irregularities may not affect the integrity of completed welds, they are frequently governed by specification requirements and are subject to inspection.

Pores occasionally form in the face of a weld bead. The pattern can vary from a single pore every few inches to many pores per inch. It is important to eliminate surface pores because they can result in slag entrapment during subsequent passes. Sound multiple-pass welds are not normally achieved unless surface pores are removed prior to depositing the next weld layer.

The pores are caused by improper welding conditions such as excessive current, inadequate shielding, or use of the wrong polarity. Unsatisfactory gas shielding may also adversely affect the weld surface. Gas shielding is usually better at the bottom of a weld groove than near the top of the groove. Improvement in the appearance of the weld bead may be achieved by changing such welding conditions as polarity or arc length.

Acceptable weld surfaces are often judged by comparison with samples. As an illustration, a fillet weld with poor surface appearance is shown in Figure 13.23(A), while a satisfactory weld is shown in Figure 13.23(B).

Undercut

Undercut consists of a groove melted into the base metal adjacent to the weld toe or root and left unfilled by weld metal. The term *undercut* is sometimes used in the shop to describe the melting away of the groove face

(A)

(B)

Figure 13.23—(A) Single-Pass Horizontal Fillet Weld with Surface irregularities Caused by Improper Welding Technique and (B) Single-Pass Horizontal Fillet Weld Created with the Proper Welding Technique

of a joint at the edge of a layer or bead of weld metal. This "undercut" forms a recess in the joint face where the next layer or bead of weld metal must fuse to the base metal. If the depth of fusion at this location is too shallow when the next layer of weld metal is applied, voids may be left in the fusion zone. These voids are more correctly identified as instances of incomplete fusion.

Shown in Figures 13.2 and 13.5, undercut is typically located parallel to the junction of weld metal and base metal at the toe or root of the weld. This discontinuity creates a mechanical notch at the weld interface. Careful examination of welds will reveal that most have some undercut. However, undercut may often be seen only in metallographic tests in which etched weld cross sections are examined under magnification. Undercut is usually not deleterious when it is controlled within the limits of the specifications and does not constitute a sharp or deep notch.

Undercut is generally associated with improper welding procedures and techniques and excessive welding current, voltage, or a combination of these. Table 13.9 presents an overview of the common causes of undercut and suggested remedies.

Table 13.9
Undercut—Common Causes and Remedies

Causes	Remedies
Excessive welding current	Reduce welding current
Excessive travel speed	Reduce travel speed
Poor electrode manipulation	Additional welder training

Underfill

Underfill is a groove weld condition in which the weld face or root surface is below the adjacent surface of the base metal. It results simply from the failure to fill the joint with weld metal as specified in the welding procedure specification or on the design drawing. Normally, the condition is corrected by adding one or more additional layers of weld metal in the joint prior to acceptance for use.

Base Metal Discontinuities

Not all discontinuities are the result of improper welding procedures. Many difficulties with weld quality may be traced to the base metal. Base metal requirements are usually prescribed by an American Society for Testing and Materials (ASTM) specification.[17] Departure from these requirements should be considered cause for rejection.

Base metal properties that should meet specification requirements include chemical composition, cleanliness, laminations, surface conditions (e.g., scale, paint, oil), mechanical properties, and dimensions. Inspectors should keep these factors in mind when evaluating welded joints for the sources of indications that have no apparent cause. Common base metal discontinuities are described below.

Laminations. Laminations in plate and other mill shapes are flat, generally elongated discontinuities found in the central zone of wrought products. Laminations may be completely internal and only detectable by ultrasonic tests, or they may extend to an edge or end where they may be visible at the surface. They may also be exposed when the base metal is cut.

17. American Society for Testing and Materials (ASTM), *Annual Book of ASTM Standards*, West Conshohocken, Pennsylvania: American Society for Testing and Standards.

Delamination. Delamination in the base metal may occur when laminations are subject to transverse stresses. The stresses may be residual from welding, or they may result from external loading. Delamination can be detected at the edges of workpieces during visual inspection or by means of ultrasonic testing using longitudinal waves through the thickness. Delaminated metal should not be subjected to tensile loads.

Lamellar Tears. Some rolled structural shapes and plates are susceptible to a cracking defect known as a *lamellar tear.* Illustrated schematically in Figure 13.24, lamellar tears are terrace-like separations in the base metal. Lamellar tearing, a form of fracture resulting from high stress in the through-thickness direction, may extend over long distances. It is typically caused by the thermally induced shrinkage stresses resulting from welding.

The tears occur roughly parallel to the surface of rolled products. They generally initiate either in regions having a high incidence of coplanar, stringer-like, nonmetallic inclusions or in areas subject to high residual stresses, or both. The fracture usually propagates from one lamellar plane to another by shear along planes that are nearly normal to the rolled surface.

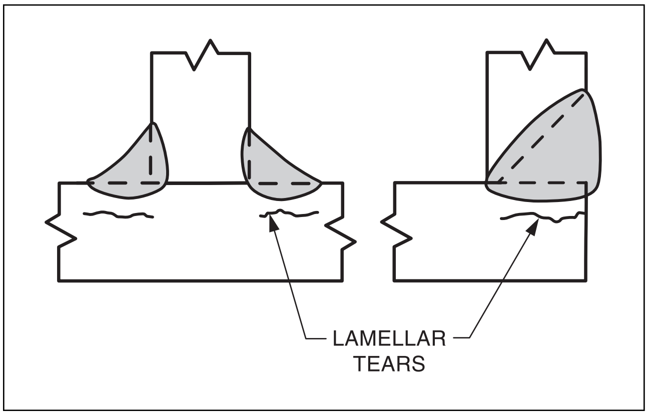


Figure 13.24—Schematic Illustration of Lamellar Tearing

Laps and Seams. Laps and seams are longitudinal flaws that occur at the surface of the base metal. They may be found in hot-rolled mill products. A lap is a surface imperfection that is caused by folding over hot metal, fins, or sharp corners and then rolling or forging these into the surface. A seam is an unwelded fold or lap that appears as a crack on the surface of a metal product, usually resulting from a discontinuity formed during casting or rolling. These can be harmful in applications involving welding, heat-treating, or upsetting as well as in certain components that are to be subjected to cyclic loading.

When the flaw is parallel to the principal stress, it is not generally considered a critical defect. If the lap or seam is perpendicular to the applied or residual stresses, or both, it may propagate as a crack. Although laps and seams are surface discontinuities, their presence may be masked by manufacturing processes that have subsequently modified the surface of a mill product.

Open laps and seams can be detected by magnetic particle, penetrant, and ultrasonic inspection methods. However, those that are tightly closed may be missed during inspection. Welding over these discontinuities can cause porosity, incomplete fusion, and cracking. Thus, these discontinuities must be removed prior to welding. Mill products can be produced with special procedures to control the presence of laps and seams.

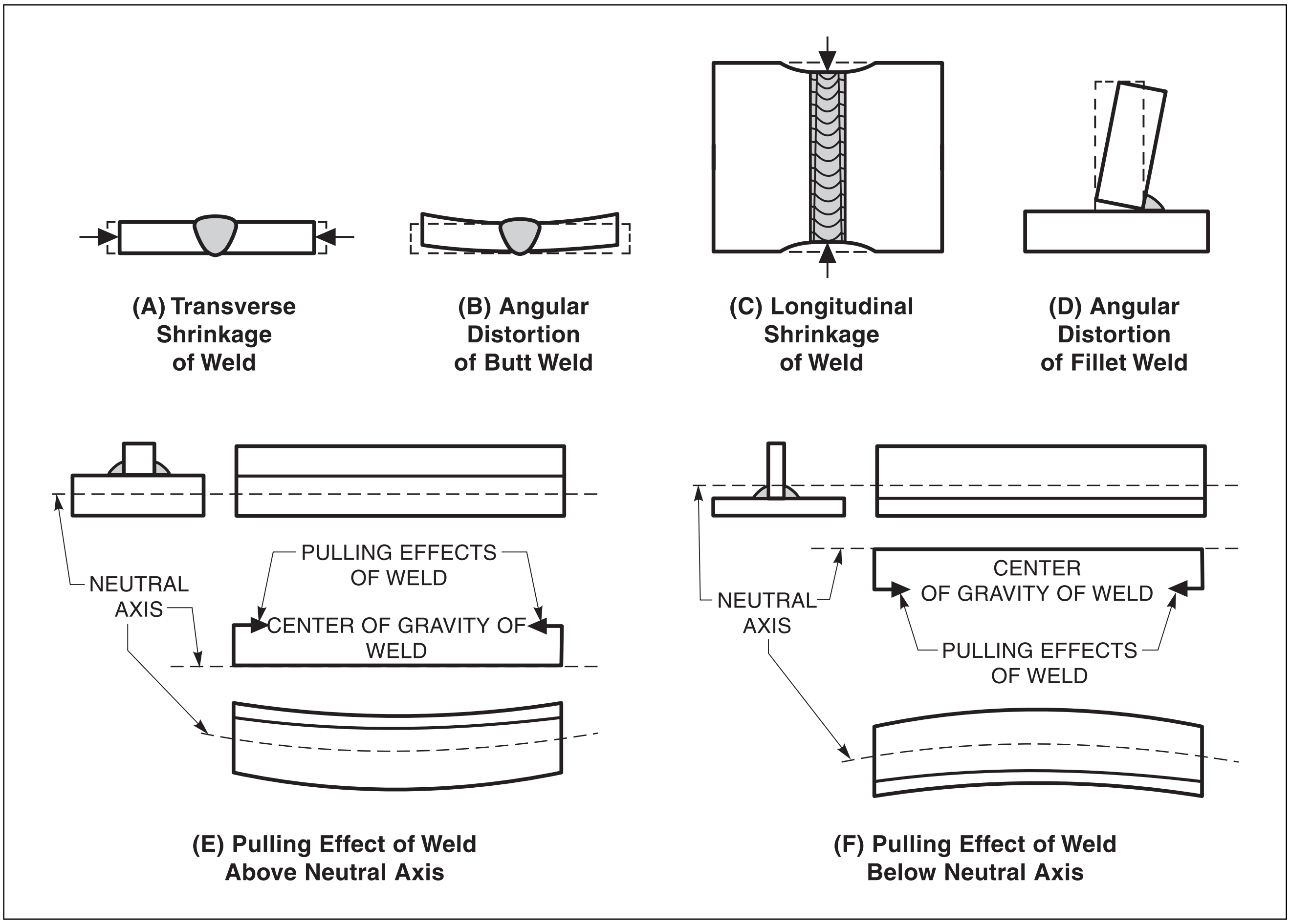
Dimensional Discrepancies

The production of satisfactory weldments depends on maintaining specified dimensions, whether these pertain to the size and shape of welds or the finished dimensions of an assembly. Requirements of this nature are found in the drawings and specifications. Departures from the requirements in any respect should be regarded as dimensional discrepancies which, unless a waiver is obtained, must be corrected before acceptance of the weldment. Dimensional discrepancies can be largely avoided if proper controls are exercised when the base metals are cut to size.

Distortion. Distortion involves the buckling of sheet or plates parallel or transverse to the weld axis. The various types of distortion are depicted in Figure 13.25. As shown in Figure 13.25(A), transverse shrinkage of the weld is distortion perpendicular to the axis of the weld. Angular distortion in a butt joint, depicted in Figure 13.25(B), results from the rotation of the base metal about the longitudinal axis of the weld. As shown in Figure 13.25(C), longitudinal shrinkage is distortion parallel to the weld axis. Figure 13.25(D) depicts angular distortion in a fillet weld, which occurs as a result of the rotation of one member about the longitudinal axis of the weld. Figures 13.25(E) and (F) show the pulling effect of the weld above and below the neutral axis, respectively. This occurs when both components rotate relative to the central axis of the weld.

Distortion can generally be controlled by using the proper welding processes, welding sequences, preheat or by aligning the workpieces in suitable fixtures prior to welding. The actual method employed should be dictated by the size and shape of the workpieces as well as by the thickness of the metal.

Incorrect Joint Preparation. Established welding practices require proper dimensions for each type of joint geometry consistent with the base metal composition



Source: O'Brien, R. L., ed., 1997, *Jefferson's Welding Encyclopedia*, 18th ed., Miami: American Welding Society, Figure D-7.

Figure 13.25—Types of Distortion

and thickness and the requirements of the welding process. Departure from the required joint geometry increases the probability of weld discontinuities. Therefore, joint preparation should meet the requirements of the shop drawings and be within the specified limits.

Weld Joint Mismatch. Joint mismatch is another common discontinuity. In plate, mismatch involves offset or misalignment in a direction perpendicular to the plate surface and weld axis. In pipe, offset or mismatch occurs in the radial direction at a butt joint or a T-joint. Excessive mismatch is a result of improper fitup, fixturing, tack welding, or a combination of these factors.

This term is often used to denote the amount of offset or mismatch across a butt joint between members of equal thickness. Many codes and specifications limit the amount of allowable offset because mismatch can result in stress raisers at the toe and the root of the weld.

Incorrect Weld Size. With respect to fillet welds, the required size of the welds should be specified on the detailed drawings. Fillet weld size can be measured with gauges designed for this purpose. Oversized fillet welds are not harmful provided they do not interfere with subsequent assembly. They are not economical, however, and can cause excessive distortion.

The size of a groove weld is dependent on its joint penetration, which is defined as the depth of the joint preparation plus root penetration. Incorrect weld sizes include undersized, oversized, and underfilled welds. Undersized fillet welds can be corrected by adding one or more weld passes. Underfilled groove welds can be repaired by performing additional passes.

Weld Profile. The profile of a finished weld can affect the service performance of the joint. The surface profile of an internal pass or layer of a multiple pass weld can contribute to the formation of incomplete fusion or slag inclusions when the next layer is deposited. The requirements for weld profile discontinuities are usually included in the welding procedure specifications. Figure 13.26 illustrates various types of acceptable and unacceptable weld profiles in fillet and groove welds.

Inadequate Weld Joint Properties

Specific mechanical properties or chemical compositions, or both, are required of all welds in a weldment. These requirements depend on the codes or specifications covering the weldment. Among the mechanical properties that must be within specifications are tensile

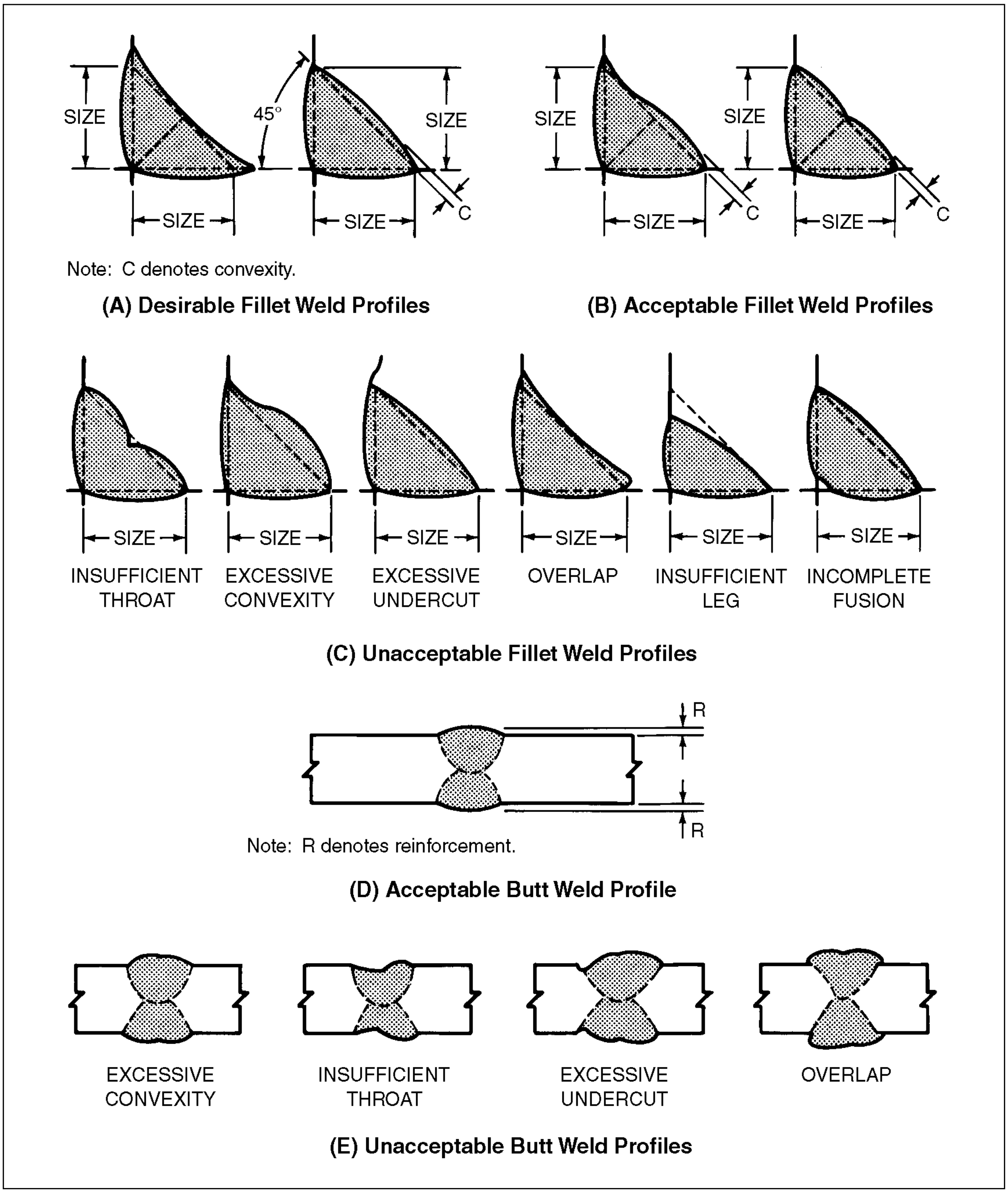


Figure 13.26—Weld Profiles of Acceptable and Unacceptable Surface Conditions

strength, yield strength, ductility, hardness, and toughness. Departure from these specified requirements results in an unacceptable weld.

Although the required properties are normally determined using specially prepared test plates, they can be determined by means of destructive testing of sample weldments taken from production. When test plates are used, the inspector should verify that standard production equipment and procedures have been followed. Otherwise, the results obtained may not represent the properties of production weldments.

The mechanical properties that may not be satisfactory include tensile strength, yield strength, ductility, hardness, and toughness. The chemical composition of the weld metal may be improper because of incorrect filler metal composition or excessive dilution or both. This condition may result in lack of corrosion resistance in the weld zone.

DISCONTINUTIES ASSOCIATED WITH RESISTANCE WELDING

With respect to spot, seam, and projection weld quality standards, the required level of quality depends primarily upon the application. Thus, the appropriate codes and standards as well as the customer's requirements should be reviewed prior to starting production welding. As some codes and standards are more stringent than others, the selection of the codes or standards to be used may have a cost impact on the project.

Once the codes and standards have been selected, they should be specified on the drawings or in the contract. The next step involved in ensuring weld quality is to obtain a through knowledge of the customer's requirements. When the customer's requirements deviate from the applicable codes or standards, these deviations should be stated in a contract document. Not all discontinuities are considered weld defects. The contract document should specify the weld quality standards or code requirements specifying the accept-and-reject criteria.

A qualified welder should always perform production welding in accordance with a qualified weld procedure. This assists in ensuring the repeatability of weld quality and performance. The work of welders and welding operators is normally qualified using both destructive and nondestructive test methods. A weld procedure is normally qualified using destructive test methods.

The most important indicators of weld quality in resistance welds are the following:

1. Surface appearance,
2. Weld size,
3. Penetration or depth of fusion,
4. Strength and ductility,
5. Internal discontinuities,
6. Sheet separation and expulsion, and
7. Weld consistency.

COMMON DISCONTINUITIES IN RESISTANCE WELDS

Most discontinuities encountered in spot, seam, and projection welding are either equipment- or process-related. Equipment-related discontinuities result from conditions related to the welding machine, the welding control system, or the electrode used. Process-related discontinuities are associated with joint configuration, surface condition, shunting of the welding current, and welding parameters.[18] The most common types of discontinuities encountered in resistance welds are described below.

Surface Appearance

The surface appearance of a spot, seam, or projection weld should be relatively smooth. In the case of contoured work, the weld surfaces should also be round or oval. They should be free from surface fusion, electrode deposit, pits, cracks, deep electrode indentation, or any other condition that would indicate improper electrode maintenance or equipment operation. The causes of undesirable spot weld surface conditions and their effects on weld quality and cost are summarized in Table 13.10.

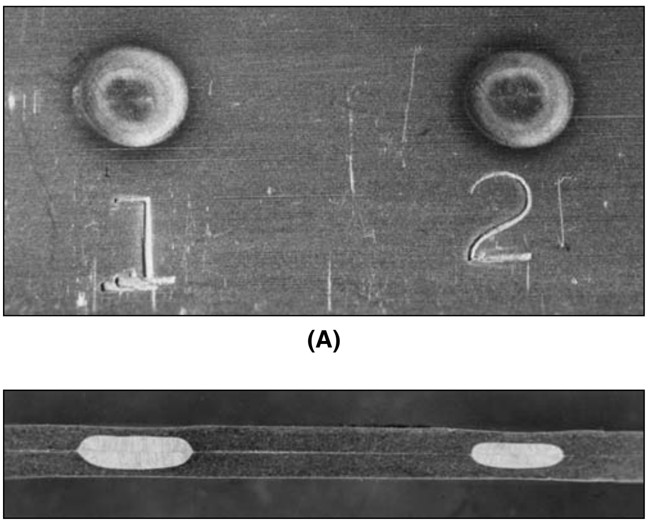
The surface appearance of a resistance weld is not an infallible indication of weld strength, size, or internal soundness. Although it is an indication of the conditions under which the weld was made, it should not be used as the sole criterion for qualifying production welds. For example, a group of spot welds in a joint may have identical surface appearance in spite of the fact that the second and succeeding spot welds may be undersized at the faying surface because of the shunting of current through the previous spot welds.

To illustrate, adjacent spot welds of a similar surface size are shown in Figure 13.27(A). However, Figure 13.27(B) reveals that the weld size at the faying surface of the first weld is greater than that of the second weld. In this case, the second weld is smaller than the first because part of the welding current passed through the first weld. Both welds have identical surface appearance because the welding current enters through the outside surface from the electrodes. The size difference is

18. For further information, see Chapter 7 in Bastian, B., ed., 1998, *The Professional's Advisor on Resistance Welding,* Miami: American Welding Society.

Table 13.10
Undesirable Surface Conditions in Spot Welds

Type	Cause	Effect
Cracks, deep cavities, or pinholes	Removing the electrode force before welds are cooled from liquids; excessive heat generation, resulting in heavy expulsion of molten metal; poorly fitting parts requiring most of the electrode force to bring the faying surfaces into contact	Reduction of fatigue strength if weld is in tension or if crack or imperfection extends into the periphery of weld area; increase in corrosion due to accumulation of corrosive substances in cavity or crack
Deep electrode indentation	Improperly dressed electrode face; lack of control of electrode force; excessively high rate of heat generation due to high contact resistance (low electrode force)	Loss of weld strength due to reduction of metal thickness at the periphery of the weld area; bad appearance
Electrode deposit on work (usually accompanied by surface fusion)	Scaly or dirty material; low electrode force or high welding current; improper maintenance of electrode contacting face; improper electrode material; improper sequencing of electrode force and weld current	Bad appearance; reduced corrosion resistance; reduced weld strength if molten metal is expelled; reduced electrode life
Irregularly shaped weld	Misalignment of work, bad electrode wear, or improper electrode dressing; badly fitting parts; electrode bearing on the radius of the flange; skidding; improper surface cleaning of electrodes	Reduced weld strength due to change in interface contact area and expulsion of molten metal
Surface fusion (usually accompanied by deep electrode indentation)	Scaly or dirty metal; low electrode force; mismatch of work; high welding current; electrodes improperly dressed; improper sequencing of pressure and current	Undersize welds due to heavy expulsion of molten metal; large cavity in weld zone extending through to surface; increased cost of removing burrs from outer surface of work; poor electrode life and loss of production time from more frequent electrode dressings



(A)

(B)

Figure 13.27—(A) Surface Appearance of Two Successive Spot Welds in 0.040 in. (1 mm) Stainless Steel Sheet; (B) Cross Section of the Same Welds, Showing the Effect of Current Shunting

greater for closely spaced welds, welds in metals having low electrical resistively, and welds in thick sheets.

Incorrect Weld Size

The diameter or width of the fused zone in the weld must meet the requirements stipulated in the drawing or design criteria in the applicable specifications. In the absence of these design criteria, either customer-approved or internal shop practices based on the following general rules should be used.

First, spot welds that are reliably reproduced under normal production conditions should have a minimum nugget diameter of 3.5 to 4 times the thickness of the thinnest outside part of the joint. In cases of three or more dissimilar thicknesses, the nugget diameters between the adjacent parts can be adjusted by the selection of the electrode shape, design, and the materials to be joined. Second, the individual nuggets in a pressure-tight seam weld should overlap a minimum of 25%. The width of the nugget should be at least 3.5 to 4 times the thickness of the thinner parts material. Third, projection welds should have a nugget size equal to or larger than the diameter of the original projection.

It is important to note that the nugget size of a spot, seam, or projection weld has a maximum limit. This limit is based on the economical and practical limitations of producing a weld and the laws of heat generation and dissipation. The maximum useful nugget size is difficult to specify in general terms. Therefore, this limit should be established in the design requirements, welding procedure, and previous shop practice.

Possible causes of incorrect weld size are inadequate weld time, low welding current, incorrect electrode force (too high or too low), improper electrode shape, improper heat balance due to dissimilar thicknesses or metal combination, and excessive line voltage fluctuation.[19]

Incomplete Joint Penetration or Depth of Fusion

The term *depth of fusion* refers to the distance the weld nugget extends into the base metal workpieces being joined. The minimum depth of fusion is generally accepted as 20% of the thicker of the workpieces being joined. If the depth of fusion is less than 20%, it is considered to be incomplete, and the weld is said to be "cold" because the heat generated in the weld zone was low. Normal variations in welding current, time, electrode force, among others, may cause undesirable changes in weld strength of "cold" welds. In extreme cases, no weld nugget may have formed.

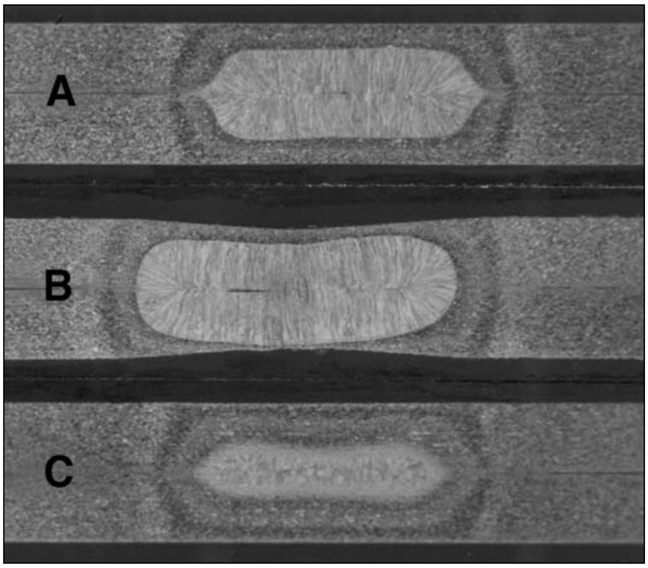


Figure 13.28—Joint Penetration/Depth of Fusion in Spot Welds: (A) Normal; (B) Excessive; and (C) Insufficient

The depth of fusion should not exceed 80% of the thinnest member of the base material being fused. Greater depth results in expulsion, excessive indentation, and rapid electrode wear. Normal, excessive, and insufficient depths of fusion are shown in Figure 13.28. The depth of fusion of each weld should be approximately uniform for equal or nearly equal sheet thicknesses. For dissimilar thickness ratios of 3 to 1 and greater, the depth of fusion into the thicker piece need not exceed that of the thinner base metal material.

Incomplete joint penetration or depth of fusion results from failing to adhere to optimal weld parameters, the presence of contamination at the joint interface, defects in the equipment, or a combination of these. This discontinuity can be remedied by using proper procedures and adhering to the recommended maintenance practices.

Incorrect Strength and Ductility

Structures employing spot, seam, and projection welds are usually designed so that the welds are loaded in shear when the parts are exposed to tension or compression loading. In some cases, welds may be loaded in tension when the direction of loading is normal to the plane of the joint. In others, the welds may be loaded in combinations of tension and shear. For example, in the case of flanged tank sections that are resistance seam welded along the flanges, the seam welds may be subjected to peeling action when the tank is pressurized.

The joint most often used for spot welding is the lap joint. The joint overlap has a minimum requirement, which is based on the nugget size, and is directly related to the size of the electrode. The distance from the centerline of the nugget to the edge of the base metal being fused is referred to as the *edge distance*. The edge distance should be at least 1.5 times the nugget diameter.

The spacing or "pitch" between the spot welds and the spacing between the roll seam welds are also important. It is normally specified in the weld symbol drawing. The pitch is measured from the centerline of a spot weld to the centerline of an adjacent spot weld. The pitch is normally 3 to 7 times the nugget size and does not exceed 10 times the nugget size. The separation between the sheets being fused should not exceed 10% of the thinnest sheet. If the weld nuggets of a seam weld overlap, they will be watertight; if they do not, water can escape or seep from between the welds.

The strength requirements for spot and projection welds are normally specified in pounds (kilograms) per weld. For seam welds, the strength is usually specified in pounds per inch (kg/mm) of joint length. It is good practice to specify a weld strength that is greater than

19. Bastian, B., ed., 1998, *The Professional's Advisor on Resistance Welding*, Miami: American Welding Society, p. 58.

that of welds of minimum recommended nugget size, but not more than 150% of such welds.

The strength of spot and projection welds increases as their diameter becomes larger although the average unit stress decreases. The unit stress decreases because of the tendency for failure to occur at the edge of the nugget as its size increases. In low-carbon steel, for example, the calculated average shear stress in good welds at rupture varies from 10 kips per square inch (ksi) to 60 ksi (69 megapascal [MPa] to 414 MPa). Low values apply to relatively large welds, whereas high values apply to relatively small welds. In both instances, the actual tensile stress in the sheet at the weld periphery is at or near the ultimate tensile strength of the base metal. This factor tends to cause the shear strength of circular welds to vary linearly with diameter.

Single spot and projection welds are not strong in torsion when the axis of rotation is perpendicular to the plane of the welded parts. This strength tends to vary with the cube of the weld diameter. Little torsion deformation is obtained with brittle welds prior to failure. Angular displacements may vary from 5° to 180°, depending on the ductility of the weld metal. Torsion is normally used to shear welds across the interface to measure the nugget diameter. Periodic testing of production spot welds verifies that weld schedules are producing adequate weld sizes.

The ductility of resistance welds is determined by the composition of the base metal and the effect of high temperatures and subsequent rapid cooling rates on the weld and base metals. However, the standard methods of measuring ductility are not adaptable to spot, seam, and projection welds. The closest approximation to a ductility measurement is a hardness test, considering that the hardness of a metal is usually an inverse indication of its ductility. For a given alloy, ductility decreases with increasing hardness, but different alloys of the same hardness do not necessarily possess the same ductility. Another method of determining the ductility of spot or projection welds of equal size is to determine the ratio of direct tensile strength to tension-shear strength. A weld with good ductility has a high ratio; a weld with a poor ductility has a low ratio.

Various methods can be used in production welding to minimize the hardening effect of rapid cooling. These include (1) using long weld times to introduce heat into the work, (2) preheating the weld area with a preheat current, (3) tempering the weld and heat-affected zones using a temper cycle at some interval after the weld time, and (4) furnace annealing or tempering the welded assembly.

These methods are not always practical, however. For instance, the first produces greater distortion of the assembly and reduces production rates. The second and third methods require welding machine controls that provide these features, whereas the fourth technique involves an additional operation that reduces the strength of a cold-worked base metal. Quenching a welded assembly from the annealing temperature may cause excessive distortion.

Internal Discontinuities

Internal discontinuities include cracks, porosity, cavities, and, in some cases, inclusions in the weld nugget. As a rule, these discontinuities have no detrimental effect on the static or fatigue strength of the weld if they are located entirely in the central portion of the weld nugget. On the other hand, it is a cause for concern when a defect or discontinuity of this nature occurs at the periphery of a weld where the load stresses are highly concentrated.

Spot, seam, and projection welds in metal thicknesses of approximately 0.040 in. (1 mm) and greater may have small shrinkage cavities in the center of the weld nugget. This is illustrated in Figure 13.29(A). These cavities are less pronounced in some metals than in others due to the difference in forging action of the electrodes on hot metal. Such shrinkage cavities are generally not detrimental in the usual applications. However, the cavity that results from the heavy expulsion of molten

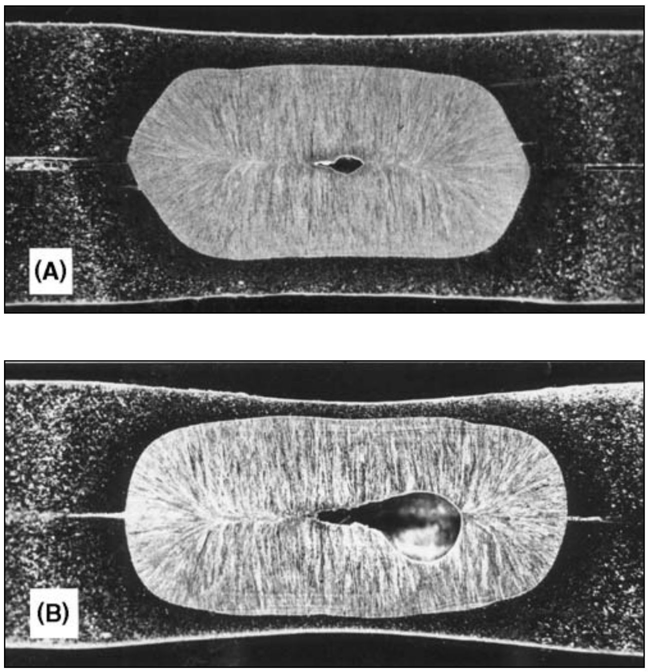


Figure 13.29—Shrinkage Cavities in Spot Welds: (A) Small; (B) Large

metal, as shown in Figure 13.29(B), may take up a very large part of the fused area and is detrimental.

A certain number of expulsion cavities are to be expected in the production welding of most commercial steels. The heavy expulsion of molten metal is a result of improper welding conditions. The acceptable number of welds with expulsion cavities should be limited by specification. The best method of assuring satisfactory adherence to specified spot welding schedules is a structured statistical quality control program with regular production sampling and destructive testing.

Internal discontinuities in spot, seam, and projection welds are generally caused by low electrode force, high welding current, or any other conditions that produce excessive welding heat. Removing the force of the electrode too soon after stopping the welding current also causes internal defects. When this occurs, the weld nugget is not properly forged during cooling. This phenomenon may occur during high-speed seam and roll spot welding. These discontinuities can be prevented by adhering to the recommended welding parameters.

Excessive Sheet Separation

The term *excessive sheet separation* refers to the distance that remains between the faying surfaces adjacent to the weld after a spot, seam or projection weld has been made. This discontinuity occurs as a result of the expansion and contraction of the weld metal and the forging effect of the electrodes on the hot nugget. The amount of separation varies with the thickness of the base metal.

Excessive sheet separation results from the same causes as surface indentation or deep electrode indentation, to which it is related. Improperly dressed electrode faces can act as punches under high electrode force. This tends to decrease the joint thickness, radically upset the weld metal, and force the sheets up around the electrodes. This discontinuity can also be caused by excessive welding current, improper fitup, and inadequate weld force. Excessive sheet separation is illustrated in Figure 13.30, in which one sheet is laminated.

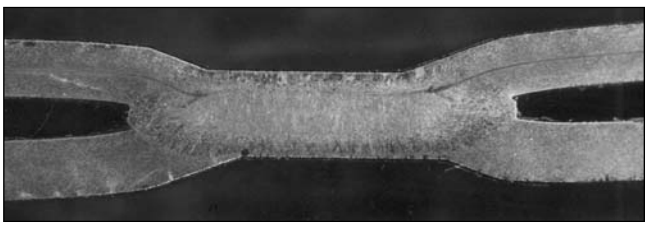


Figure 13.30—Excessive Sheet Separation

Expulsion

Expulsion involves the forceful ejection of molten metal, particularly from the faying surfaces of resistance, seam, spot, and projection welds. Expulsion of the weld metal is the result of overheating, generally from the use of excessive welding current. This is particularly true when the high current is combined with inadequate electrode force, improperly faced electrodes, or inadequate follow-up of the electrodes. This discontinuity may also arise due to contaminated surfaces.

Expulsion results in internal cavitation, which typically reduces weld strength. This tendency is so pronounced that the maximum current is normally limited to a value at which expulsion cannot occur. To prevent the occurrence of expulsion, the proper electrode force, current, and voltage should be used, and surface contamination should be eliminated.

MAINTAINING CONSISTENT RESISTANCE WELD QUALITY

Consistent resistance weld quality can be maintained with proper control of the factors that tend to produce variations in the final product. These factors should be addressed when qualifying the welding procedure specification. The factors include the following:

1. Joint design and fitup;
2. Material thickness tolerance;
3. Composition, temper, and surface condition of the base metal;
4. Electrode material and shape;
5. Electrode and weldment cooling;
6. Welding cycle variables; and
7. Postweld thermal treatments.

The importance of joint design and fitup is discussed elsewhere in this chapter. Large variations in workpiece thickness, particularly with three or more thicknesses, may produce an inconsistent fitup, which can affect weld quality. Changes in the composition or temper of the base metal or surface conditions require a revision of the welding schedule to produce acceptable welds.

Resistance welds of consistent quality are obtained by implementing the appropriate welding settings and techniques and by maintaining these for the duration of a particular production run. Factors such as welding current, weld time, and electrode force must be controlled within the limits of the schedule. The best control method involves the periodic testing of workpieces or test samples.

The number of workpieces tested as well as the test method may vary. The test specimens may be examined nondestructively, or a certain number may be tested using destructive testing methods. Statistical methods are then used to predict the quality of the production lot. In any case, an inspector must be able to recognize conditions that may cause variations in weld quality, ensure that test specimens are representative samples, and verify that production pieces are fabricated under the same conditions as the test specimens.

The application of statistical control[20] to production quality has three primary objectives—to reduce the number of rejections and machine shutdowns because of poor performance, to assist in establishing the optimum procedure limits for satisfactory quality, and to provide a reasonable, reliable measure of actual production quality. The attainment of these objectives should contribute to the fabrication of high-quality products at an economical rate and with minimum scrap.[21]

DISCONTINUITIES ASSOCIATED WITH THE SOLID-STATE WELDING PROCESSES

Certain solid-state welding processes are performed without the addition of filler metal at temperatures essentially below the melting point of the base metals being joined. When the joint reaches the desired welding temperature, force is applied to generate the weld. As welding is being accomplished, some molten metal may be generated between the surfaces being joined, but it is expelled as a result of the pressure applied on the joint during the welding cycle. The resulting welds are all characterized by a flat weld interface.

Thus, the discontinuities most commonly associated with the solid-state welding processes are two-dimensional and in the plane of the joint. However, cracks can occur in other orientations. With respect to inspection, some examination methods that are used for fusion welds—radiographic and ultrasonic examination, for example—require special techniques when applied to these welds, and the interpretation of the examination results is more challenging.

COMMON SOLID-STATE WELD DISCONTINUITIES

The discontinuities encountered in solid-state welded joints can be classified as either mechanical or metallurgical in origin. Mechanical problems are the dominant cause for the rejection of solid-state welds. The discrepancies caused by mechanical problems are readily identified by visual inspection and can usually be corrected by equipment adjustments. Metallurgical discontinuities are usually associated with material defects or heterogeneities. These discontinuities are difficult to detect with nondestructive examination methods.

The various types of metallurgical discontinuities include the following:

1. Cracks,
2. Intergranular oxidation,
3. Decarburization,
4. Voids,
5. Inclusions,
6. Cast metal at the interface,
7. Flat spots, and
8. Out-turned fibrous metallurgical structures at the weld.

Mechanical and metallurgical discontinuities are discussed in more detail below.

Weld Joint Mismatch

Weld joint mismatch, resulting from the misalignment of the joint members, is a mechanical discontinuity. Figure 13.31 illustrates both an unacceptable weld caused by mismatch or offset of the workpiece and an acceptable weld.

Insufficient Upset

In the case of flash[22] and upset welds, the shape and contour of the upset metal are a good indicator of weld quality. The term *upset* refers to the bulk deformation resulting from the application of pressure in welding. The geometry of the weld in Figure 13.32(A) indicates proper heat distribution as well as proper upset. Insufficient upset, as shown in Figure 13.32(B), could indicate trapped oxides or flat spots (see below) at the weld interface and possibly an incomplete weld.

The remedies for this discontinuity include increased flashing time or upset distance, which may entail a modification of the workpiece design.

20. The basic principles of statistical control are widely used in industry. Briefly, these principles are (1) select samples of actual production and test them for performance to specifications, (2) estimate the probable quality or conformance of all production by the analysis of samples, and (3) predict future quality by considering the trends set by past and present quality.

21. The advantages, methods, and procedures for statistical quality control of resistance welding are described in American Welding Society (AWS) Committee on Resistance Welding, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1, Miami: American Welding Society.

22. Although flash welding is not categorized as a solid-state process, the example given here is valid.

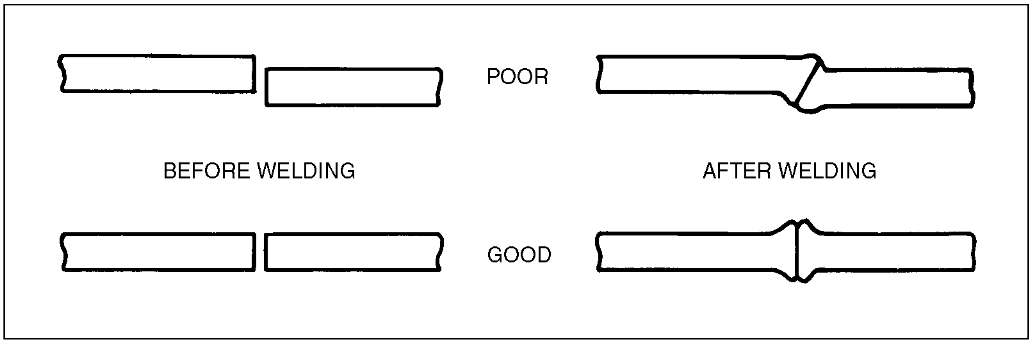


Figure 13.31—Effect of Workpiece Alignment on Joint Geometry

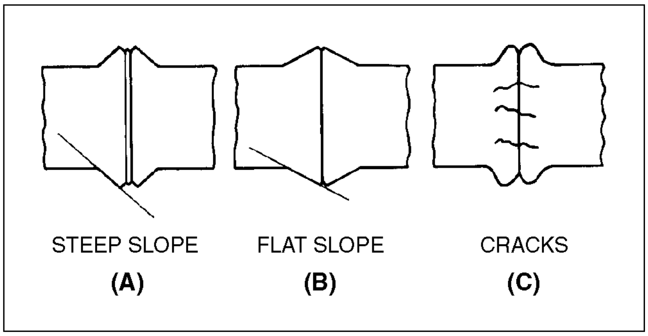


Figure 13.32—Visual Indications of Flash Weld Quality: (A) Satisfactory Heat and Upset; (B) Insufficient Heat or Upset or Both; and (C) Cracks due to Insufficient Heat

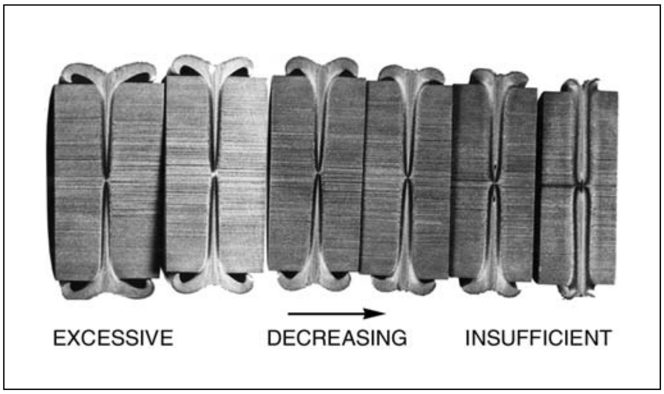


Figure 13.33—Effects of Axial Shortening on Weld Quality in Friction Welds

The condition and the shape of the upset on friction weldments are indicators of possible discontinuities along the weld interface. Figure 13.33 shows the effect of axial shortening on weld quality. These inertia friction welds were produced with the same speed and inertial mass but with decreasing heating pressure from left to right. Two of the welds exhibit center discontinuities because the axial shortening (pressure) was insufficient. In continuous-drive friction welds, welding may be incomplete at the center of the joint when the speed is inadequate.

Cracking

Cracking in solid-state welds can be divided into two categories—hot cracking and cold cracking—depending upon the temperature of formation. Cold cracking, illustrated in Figure 13.32(C), can be caused by insufficient heating prior to or during upsetting. Excessive cooling rates in hardenable steels can cause cold cracking, but slow cooling rates eliminate it. The most common form of hot cracking in upset welds occurs as microfissures in the heated zone.

Intergranular Oxidation

A form of intergranular oxidation known as *die-burn* can occur at clamp locations in flash welds. This discontinuity is caused by localized heating of the portion of the workpiece that contacts the clamping dies. Precleaning of the surfaces of the workpiece in the clamping area usually eliminates this concern. Excessive initial spacing between the clamping dies can result in the overheating of the workpieces near the faying surfaces during flashing. This may result in intergranular oxidation as well as nonuniform upsetting and joint mismatch.

Decarburization

Another type of solid-state discontinuity results from elemental redistribution during welding. In carbon steel, this may be manifested as decarburization, which appears as a bright band on a polished and etched surface of an upset welded steel specimen that is cut transverse to the weld interface.

Voids, Inclusions, and Cast Metal along the Weld Joint Interfaces

Voids, inclusions, and cast metal along the interfaces of the weld joint are related by the fact that they can usually be eliminated by increasing the upset distance. In the case of flash welds, craters (voids) are formed on the faying interfaces by the expulsion of molten metal during flashing. If the flashing voltage is too high or the platen motion is incorrect, violent flashing can cause deep craters in the faying surfaces. Molten metal and inclusions may be trapped in these deep craters and not expelled during upsetting.

Flat Spots

Flat spots, zones of low ductility, may be the result of a number of metallurgical phenomena having inherently different mechanisms. The smooth, irregular areas indicated by the arrows in Figure 13.34 are typical flat spots. Flat spots along the weld interface are associated with the characteristics of the base metal as well as with welding process variables.

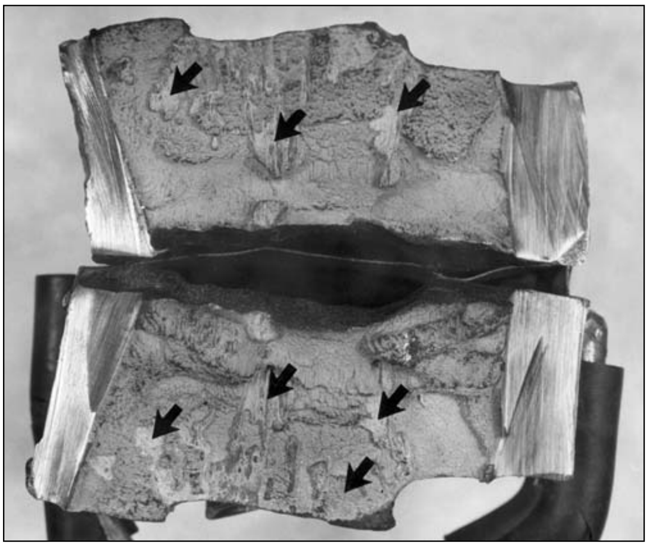


Figure 13.34—Flat Spots (Indicated by Arrows) on the Faying Fractured Surfaces of a Flash Weld

Out-Turned Fibrous Metallurgical Structures at the Weld

The inherent fibrous structure of wrought mill products may cause anisotropic mechanical behavior. An out-turned fibrous structure at the weld interface often results in some decrease in mechanical properties, particularly ductility, as compared with the base metal. The decrease in ductility is not normally significant unless one or both of the following conditions are present:

1. The base metal is extremely inhomogeneous. Examples include severely banded steels, alloys with excessive stringer-type inclusions, and mill products with seams and cold shuts produced during the fabrication process; and
2. The upset distance is excessive. When excessive upset distance is employed, the fibrous structure may be completely reoriented transverse to the original structure.

DISCONTINUITIES IN BRAZED AND SOLDERED JOINTS

Brazing and soldering rely on capillary action to draw liquid filler metal into a controlled joint clearance and on the wetting of the faying surfaces by the liquid filler metal. The two processes differ only in filler metals used and temperatures employed. The discontinuities found in soldered joints and their causes and remedies are similar to those in brazed joints. Therefore, the following discussion pertains to both brazed and soldered joints unless otherwise indicated.[23]

COMMON DISCONTINUITIES

When defining the acceptance limits for the discontinuities found in brazed and soldered joints, the shape, orientation, and location (surface or subsurface) of the

23. For further information on discontinuities in brazed and soldered joints, refer to Oates, W. R., ed., 1996, *Materials and Applications—Part 1,* Vol. 3 of *Welding Handbook,* 8th ed., Miami: American Welding Society; AWS Committee on Brazing and Soldering, 20XX, *Brazing Handbook,* 5th ed., Miami: American Welding Society; and Vianco, P. T., 1999, *Soldering Handbook,* 3rd ed., Miami: American Welding Society.

discontinuity as well as its relationship to other discontinuities should be considered. The limits of acceptability should be clearly specified when nondestructive examination is performed to identify discontinuities.

Discontinuities found in brazed and soldered joints indicate that the brazing procedure has not been appropriately controlled or that improper techniques have been used. Judgments regarding the disposition of components containing discontinuities should be made by persons who are competent in the fields of brazing metallurgy and design and who fully understand the function of the component. All dispositions should be properly documented.

The discontinuities commonly encountered in brazed and soldered joints are listed and described below. Several typical discontinuities are pictured to facilitate their recognition.

Lack of Fill

Lack of fill in the form of voids or porosity reduces the strength of the joint by reducing the load-carrying area. This discontinuity may provide a path for leakage in brazed or soldered joints designed for pressure- or liquid-containing applications. Lack of fill can result from improper cleaning of the base metal, excessive joint clearance, insufficient filler metal, entrapped gas, or the movement of the faying surfaces of the workpieces before the filler metal has solidified.

Lack of fill in a brazed lap joint is illustrated in Figure 13.35. The assembly shown in Figure 13.35(A) is composed of two flat pieces of low-carbon steel brazed with a silver brazing filler metal. In the radiograph taken through the joint, presented in Figure 13.35(B), large voids can be seen as dark areas. Cross sections 1-1 and 2-2 through the joint are shown in Figure 13.35(C). The voids in the joint capillary are evident.

A large void in the fillet of a section through a brazed copper lap joint is shown in Figure 13.36. This flawed joint was detected by bubble-testing the assembly with compressed air in a water tank. The discontinuity could have been caused by underheating or improper fluxing procedures, or both. The filler metal would not exhibit irregular flow into the joint if the brazing temperature and fluxing procedure were correct. The appropriate brazing temperature and fluxing procedure would prevent the irregular flow of the filler metal into the joint.

A brazed copper socket joint is shown in Figure 13.37(A). A radiograph of the joint, presented in Figure 13.37(B), indicates that large areas of the joint are void of filler metal. A macrograph (taken at 100X magnification using nital) of a cross section through the brazed fillet showing an extensive void in the capillary of the joint is shown in Figure 13.37(C). The voids throughout the joint were caused by insufficient heating. If a joint leaks, voids may be detected with a pressure test.

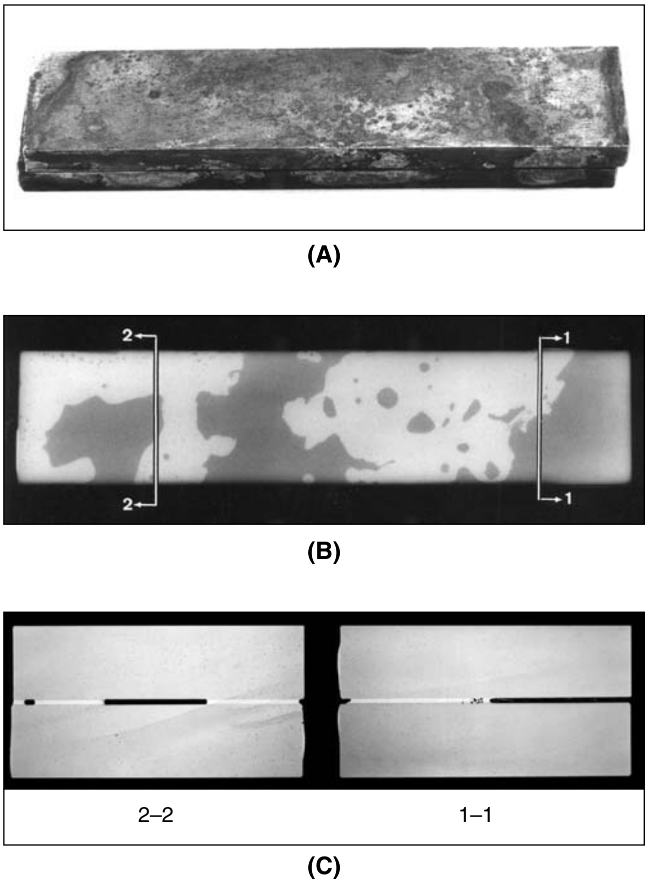


Figure 13.35—(A) Brazed Lap Joints; (B) Radiograph Indicating Voids (Dark Areas in the Joint); (C) Cross Sections through the Joint Indicating Voids in the Capillary

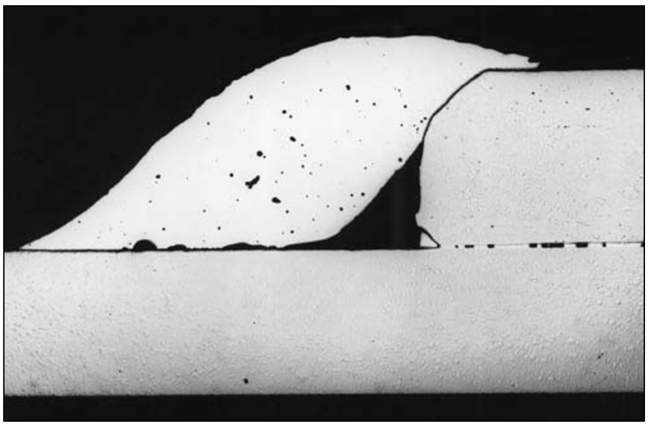
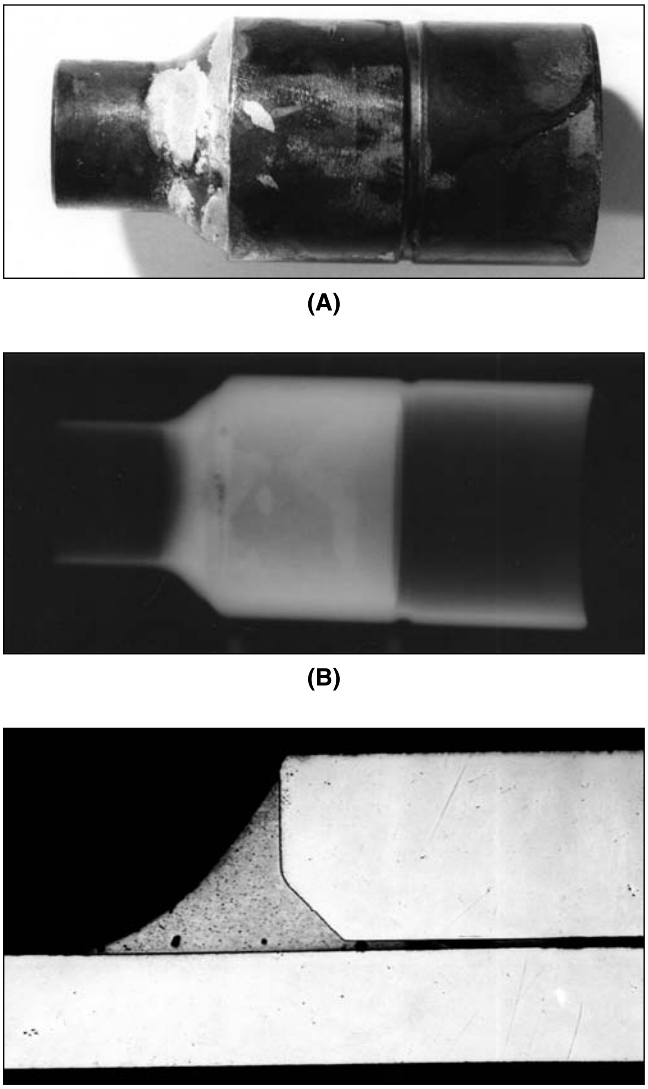


Figure 13.36—Void under the Filler Metal Fillet in a Brazed Copper Lap Joint



(A)

(B)

(C)

Figure 13.37—(A) Brazed Copper Socket Joint; (B) Radiograph of Joint; and (C) Cross Section Through the Brazed Fillet and Capillary (100X Magnification, Nital)

Flux Entrapment

Entrapped flux may be found in brazed or soldered joints in which flux is used to prevent and remove oxidation during the heating cycle. Entrapped flux prevents the flow of filler metal into that particular area, thus reducing the joint area. It may also cause false leak- or pressure-proof test acceptance. If it is corrosive, the entrapped flux can reduce service life. The appropriate brazing temperature and fluxing procedure would prevent the irregular flow of the flux into the joint.

Discontinuous Fillets

Discontinuous fillets, which are segments of joints containing undersized fillets or no fillets at all, are usually found during visual inspection. These joints may or may not be acceptable, depending upon the specification requirements of the brazed joint. Discontinuous fillets may be caused by improper fluxing, surface contamination, improper temperature, or the use of the incorrect filler metal.

Erosion of the Base Metal

Erosion of the base metal can cause undercut or the disappearance of the faying surface. It may also decrease the strength of the joint by changing the filler metal composition and reducing the cross-sectional area of the base metal. This discontinuity is caused by the filler metal's alloying with the base metal during brazing or soldering.

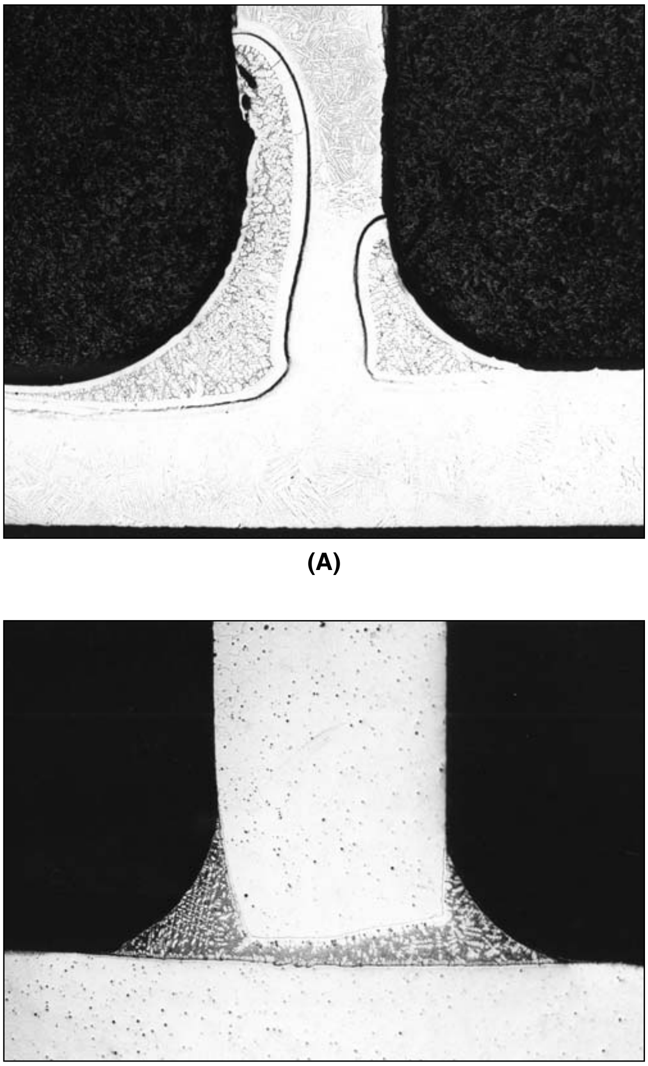
A section through a brazed joint in which severe erosion of the base metal occurred is shown in Figure 13.38(A). This erosion resulted from overheating of the joint during brazing. Although erosion may not be serious in thick sections, it cannot be tolerated in relatively thin sections. For purposes of comparison, a joint with essentially no erosion is shown in Figure 13.38(B).

Unsatisfactory Surface Appearance

Excessive flow of brazing or soldering filler metal onto the base metal, surface roughness, and excessive filler metal may be detrimental for several reasons. In addition to cosmetic considerations, these can act as stress concentrations or corrosion sites. They may also interfere with the inspection of the brazement. This discontinuity may result from improper fluxing, surface contamination, improper temperature, or the use of the incorrect filler metal.

Cracks

Cracks reduce the strength of the brazement or soldered joint as well as its service life. They act as stress raisers that can cause premature failure under cyclic loading as well as lower the static strength of the brazement. Cracks may arise as a result of underheating or overheating.



(A)

(B)

Figure 13.38—(A) Severe Alloying and Erosion of the Base Metal in a Brazed Joint; (B) Brazed Joint with Essentially No Erosion of the Base Metal

SIGNIFICANCE OF WELD DISCONTINUITIES

Ever-increasing design demands are giving rise to the development of more sophisticated inspection methods and more stringent acceptance standards. In particular, the field of fracture mechanics is dedicated to the study of the fracture performance of materials containing defects. The application of fracture mechanics to acceptance standards is often referred to as *fitness for service* or *fitness for purpose*.

Ideally, acceptance standards should represent the minimum weld, braze, or solder quality that can be tolerated to assure the satisfactory performance of the product. They should be based on tests of welded, brazed, and soldered specimens containing the particular discontinuity under consideration. Correlation of these test results with allowable results should be the basis for acceptance of these particular discontinuities. A safety factor should be added to determine a final acceptance standard. Fitness-for-service acceptance standards are a reality in limited applications and require a thorough design, metallurgical, and fracture mechanics review before implementation.

Current welding standards are based on the soundness that can be achieved with readily attainable good quality work. As they are not based on engineering principles, they may be inadequate or overly conservative. Inadequate quality standards can result in poor quality production, whereas overly conservative standards can result in failure to meet production schedules and high production costs. Despite these drawbacks, the current standards have withstood the test of time. Thus, designers can be relatively certain that the current standards will provide a satisfactory structural performance in the future.

RELATIONSHIP BETWEEN DISCONTINUITIES AND MATERIALS WELDED

The effect a particular weld discontinuity has on structural integrity, economics, and safety depends to a certain extent on the metals being welded. Metals with high fracture toughness are more resistant to failure in the presence of a discontinuity than those with low fracture toughness. However, the current fabrication codes or inspection standards do not address the relationship between the mechanical properties of the metals and the allowable discontinuities. The field of fracture mechanics provides a quantitative relationship that can be used to assess the significance of a discontinuity in terms of maximum flaw size and the material fracture toughness under conditions of plane strain.

RELATIONSHIP BETWEEN DISCONTINUITIES AND MECHANICAL PROPERTIES

The effects of discontinuities on the mechanical properties are governed by the shape, size, quantity, interspacing, distribution, and orientation of the discontinuities within the weld. Because of the number of variables, any qualitative correlation between a specific class of discontinuities and mechanical properties is extremely difficult. Therefore, trends rather than direct relationships are discussed here.

The significance of a particular discontinuity in a weld depends on its intended service. A discontinuity that is innocuous under normal operating conditions may grow to a critical size in a hostile, corrosive, fatigue-inducing environment. The heat-affected zone, which often plays a major role in the determination of the mechanical properties of the joint, can render the presence of weld discontinuities less significant. The heat-affected zones of strain-hardened and precipitation-hardened base metals experience recrystallization and resolution annealing, respectively. Both also exhibit some grain growth near the fusion line. In such metals, both the strength and hardness of the heat-affected zone are diminished.

As the strength of a base metal increases, a corresponding reduction in toughness and ductility often occurs. This increases the sensitivity of the base metal to discontinuities. Ultra-high-strength steels and hard heat-affected zones in relatively soft mild steels may be extremely sensitive to small discontinuities. When welding ultra-high-strength steels, it is also difficult to match the strength and toughness of the weld to that of the base metal.

Tensile Strength

With respect to static tensile performance, welded joints fall into two categories. These are (1) joints having weld metal strengths that closely match or undermatch the strength of the base metal and (2) joints having weld metal strengths that overmatch the strength of the base metal. In laboratory tensile tests, weld discontinuities decrease the strength of the welded joints in the first category to a greater extent than they reduce the strength of those in the second category, as no reserve of additional weld strength exists to counteract the decrease in cross-sectional area. Because of the additional strength of overmatching weld metal, a certain degree of discontinuity can be tolerated before the transverse tensile properties become adversely affected. The loss in transverse tensile strength is roughly proportional to the loss in cross-sectional area. Additional cross-sectional area provided by weld reinforcement can compensate for some of this loss.

In welded joints belonging to the second category, when the number of discontinuities present increases from a few to a significant quantity, this degradation in transverse strength is accompanied by a change in the location of the fracture from the base metal to the weld metal. Ductility usually decreases proportionally to the number of the discontinuities present, though the yield strength is not significantly affected.

Nevertheless, in production weldments, cracks in high-strength weld metal are much more serious than those in low-strength, ductile weld metal. Therefore, when welding high-strength, heat-treated steels, one solution is to deposit a weld metal that has lower strength but better ductility to accommodate strains during welding. Weld metal stronger than the base metal containing cracks has no value.

Fatigue

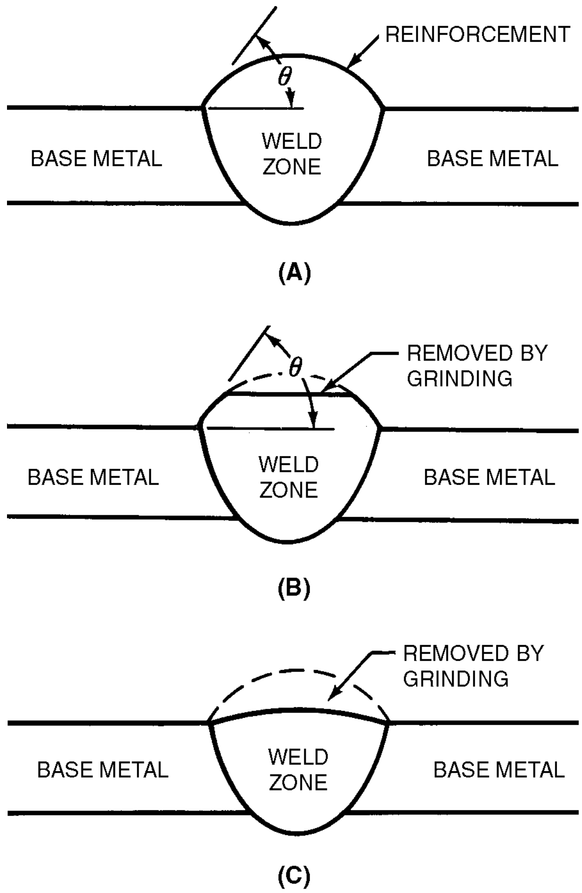
Fatigue failure at normal working stresses is invariably associated with stress concentrations. Fatigue is probably the most common cause of failure in welded construction.[24] Apart from gross cracking or extensive incomplete fusion, the discontinuities that are most significant in promoting fatigue failures are those that affect the weld faces. The combination of excessive weld reinforcement, as shown in Figure 13.39(A), and slight undercutting is one of the most serious discontinuities affecting fatigue life.

Fabrication codes usually specify the maximum permissible height of the reinforcement. Whereas the condition shown in Figure 13.39(B), in which the excess metal has been ground off without tapering the contact angle with the base metal, may meet some code requirements for maximum reinforcement, this condition does not improve the fatigue life. For service in fatigue applications, the reinforcement should blend smoothly into the base metal at the edges of the weld, as shown in Figure 13.39(C).

The effect of the contact angle of the weld reinforcement on fatigue properties is illustrated in Figure 13.40. These data demonstrate the manner in which abrupt changes in section size can affect service life. The use of a fillet-welded lap joint in place of a butt joint can reduce the fatigue strength by a factor of up to three, for example.

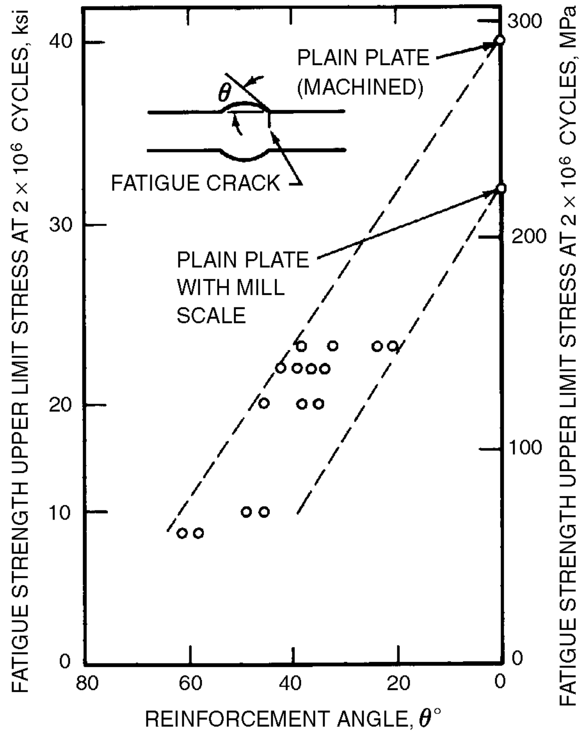
With respect to porosity, tests have shown that this discontinuity has little effect on fatigue life. Fatigue cracks initiate at the toe of the weld reinforcement. If the reinforcement is removed, porosity located on or near the surface adversely affects the fatigue strength more dramatically than subsurface porosity does. Similar tests conducted on welds with very large tungsten inclusions provided similar results except that when the reinforcement was removed, fatigue failure resulted from small oxide inclusions associated with the tungsten inclusions.

24. The design of welded structural members for fatigue applications is discussed in Chapter 5. For additional information regarding fatigue testing, see Chapter 6 of this volume.



Key:
θ = Contact angle between the base metal and the weld profile or weld reinforcement angle

Figure 13.39—(A) Weld with Excessive Reinforcement; (B) Improper Treatment of Weld Reinforcement; and (C) Acceptable Weld Reinforcement Profile for Fatigue Applications



Key:
θ = Contact angle between the base metal and the weld profile or weld reinforcement angle

Figure 13.40—Effect of the Weld Reinforcement Angle on the Fatigue Strength of Steel

Regarding slag inclusions, increasing slag-inclusion length initially leads to decreasing fatigue strength. However, when the length of the discontinuity becomes greater relative to its depth through the thickness, no further reduction in fatigue strength occurs.

Discontinuities located in the middle of the weld can be blanketed by compressive residual stress so that other smaller discontinuities nearer to the surface control the fatigue strength. These discontinuities may be below the size detectable by radiography.

Toughness

The study of fracture mechanics has permitted a relationship to be established between stresses and the size at which a discontinuity will propagate under plane strain conditions. This critical discontinuity size is inversely proportional to the square of the applied stress. The plane-strain fracture toughness of metals generally decreases as the yield strength increases.

The equations that provide the relationships between the plane-strain fracture toughness, applied stress, and the critical crack length depend on the geometry and location of the discontinuity with respect to the stress field. The location and shape (depth-to-length ratio) of the discontinuity must be known or accurately predicted, particularly when the discontinuities can grow as a result of fatigue or stress corrosion. With this information and a valid plane-strain or elastic-plastic fracture toughness value, the combination of stress and discontinuity size at which a structure can be operated safely can be estimated.

The effectiveness of a discontinuity as an initiator of fracture in a given weld metal depends on the existence of plane strain at the tip of the discontinuity. The edge radius of a discontinuity has an effect on performance. Sharp natural cracks are the most severe discontinuities. Incomplete fusion is the second most severe discontinuity. Incomplete joint penetration is not as severe as incomplete fusion if the edges of the inadequately penetrated joint are less sharp. Slag inclusions and porosity are relatively harmless in initiating brittle fracture.

The resistance of weld metal to crack propagation under impact loading is not significantly affected by porosity.

QUANTITATIVE ANALYSIS USING FRACTURE MECHANICS

The principles of fracture mechanics provide an analytical method to determine the critical crack size for unstable fracture. The most widely used model is a sharp crack whose tip is loaded under conditions of plane strain. If the stress intensity factor, K, exceeds the critical stress intensity factor for the material, K_{IC}, the crack will become unstable, and the member will fail. The plane-strain stress intensity factor, K_I, the applied or residual stress, σ, and the crack length a are related by the following equation:

$$K_I = C\sigma(\pi a)^{1/2} \tag{13.1}$$

where

K_I = Plane-strain stress intensity factor, ksi$\sqrt{\text{in.}}$ (kPa/$\sqrt{\text{mm}}$);
C = Constant, depending on discontinuity size and shape;
σ = Applied or residual stress magnitude acting on a discontinuity, ksi (kPa);
π = 3.1416; and
a = Size or depth of the discontinuity, in. (mm).

In its simplest form, the application of linear elastic fracture mechanics to fitness for service first involves the assumption of the worst case, that is, that the weld discontinuity is a crack. The plane-strain fracture toughness of the material, K_{IC}, is then determined. The vector sum of the applied and residual stresses is estimated. The critical size for unstable fracture is determined from Equation (13.1). A margin of safety is applied, and the maximum allowable cracklike flaw size is selected. Finally, acceptance criteria for more innocuous discontinuities are defined.

Two codes use linear elastic fracture mechanics to determine fitness for service. In *Rules for Inservice Inspection of Nuclear Power Plant Components*,[25] Section 11 of the American Society of Mechanical Engineers' (ASME) *Boiler and Pressure Vessel Code*,[26] fracture mechanics is used to develop acceptance criteria for weld inspections. Inspection reports contain flaw dimensions determined from nondestructive examination, and these results are compared to discontinuity standards for evaluation. The British Standards Institute's (BSI) *Guidance on Some Methods for the Deviation of Acceptance Levels for Defects in Fusion Welded Joints*, BSPD 6493,[27] provides a procedure of engineering critical assessment (ECA) that is used to establish the acceptance criteria for combinations of materials; welding processes, procedures, and consumables; and stress and environmental factors. It should be noted, however, that this engineering critical assessment can be used only in applications for which an existing fabrication code is not required by local law. Furthermore, the application of the engineering critical assessment rules must be agreed upon by all contracting parties, including local authorities, when applicable.

CONCLUSION

The basis for the selection of overall quality requirements is a combination of design, economic, safety, inspection, as well as operating and maintenance considerations that will provide the lowest cost over the full service life of the weldment. Low initial cost, minimum weight, the least amount of welding, the fewest imperfections or discontinuities, and other factors taken individually should not be the basis for the selection of quality requirements. The cost of optimum quality is derived from the following:

1. The cost of design, materials, fabrication, quality assurance, and capital expenditures;
2. The costs of possible failure multiplied by the probability of failure; and
3. Service costs, including maintenance.

As previously stated, the lowest fabrication cost seldom represents the lowest cost. The cost must include the level of quality required by the performance of the

25. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, *Rules for Inservice Inspection of Nuclear Power Plant Components,* Section 11 of *Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers.
26. See Reference 5.
27. British Standards Institute (BSI), *Guidance on Some Methods for the Derivation of Acceptance Levels for Defects in Fusion Welded Joints,* BS PD 6493, London: British Standards Institute.

product under the service conditions for which it was designed, for the full duration of its expected service life.

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28. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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CHAPTER 14

WELDING INSPECTION AND NONDESTRUCTIVE EXAMINATION

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CHAPTER 14

WELDING INSPECTION AND NONDESTRUCTIVE EXAMINATION

INTRODUCTION

This chapter addresses the inspection and nondestructive examination of joints produced by welding and related processes. The term *inspection* denotes an all-encompassing quality control activity that includes numerous steps applied at different stages during a component's fabrication and service life. Thus, this term describes activities that are performed not only at the time of manufacture but also after the component has been subjected to service. While the types of discontinuities revealed during these varying stages may differ, the basic principles governing the inspection activity are essentially the same. Consequently, the majority of the information presented in this chapter is applicable to new manufacture, repair operations, or the evaluation of components that have already been subjected to their intended service conditions.

Many of the same methods used for welding inspection are also used to determine the quality of components joined by brazing or soldering. However, because of the physical nature of brazed and soldered joints (e.g., dissimilar materials, thinness of the joint, and so forth), some of the techniques described here may be inappropriate for use with these methods. For this reason, specific techniques that are applicable to the inspection of brazed and soldered joints are also discussed in this chapter.

Members of the quality assurance community often utilize the terms *examination*, *evaluation*, and *testing* to convey a meaning similar to that of *inspection*. However, for purposes of this discussion, these terms are defined as follows:

Examination—An activity that results in the indirect measurement or determination of the quality of a material or component. Examinations can be performed without causing the destruction of the test object;

Evaluation—The consideration of examination and test results to determine the suitability of a component in terms of its quality or performance;

Testing—An activity that results in the direct measurement or determination of the suitability of a material or component for a prescribed service. Since a test involves the application of an actual or simulated service condition, the test object may be destroyed as a result of this process; and

Inspection—The overall quality control and assurance activity that encompasses other elements, including examination, testing, and evaluation.

With respect to welding inspection, the terms *discontinuity, flaw,* and *defect* are defined as follows:

Discontinuity—An interruption in the typical structure of a weldment, consisting of a lack of homogeneity in the mechanical, metallurgical, or physical characteristics of the base metal or the weld metal. A discontinuity is not necessarily a defect;

Flaw—A term nearly synonymous with *discontinuity,* but with the connotation of undesirability; and

Defect—A discontinuity that by nature or effect renders a weldment unable to meet specifications or acceptance standards. This term designates a condition that necessitates rejection.

PERSONNEL QUALIFICATIONS

In addition to possessing an in-depth knowledge and understanding of the examination and testing methods employed to evaluate the quality of weldments, welding inspectors must know and understand the basic principles of welding. They must understand all the phases of the fabrication process that apply to their product line. They should be also familiar with the job responsibilities of the engineers and other personnel involved in the manufacture of welded products.

Inspectors must have a working knowledge of applicable codes and standards to the degree necessary to evaluate the suitability of welded products when compared to fabrication requirements. Formal qualification requirements are generally required by the code or other document that specifies the inspection requirements. Standards[1] such as *Structural Welding Code—Steel,* AWS D1.1,[2] require that welding inspectors and nondestructive examination technicians be certified to meet minimum requirements with respect to education, training, experience, general technical knowledge, and visual acuity.

Recognized welding inspector certification programs include those offered by the American Welding Society (AWS) and CSA International (formerly known as the Canadian Standard Association [CSA]) based on *Standard for AWS Certification of Welding Inspectors,* ANSI/AWS QC-1[3] and *Certification of Welding Inspectors,* CSA W178.2,[4] respectively. Both of these are central certification programs in that a national body provides the qualifications review, testing, and certification.

Recognized programs for certifying nondestructive technicians include that offered by the American Society for Nondestructive Testing (ASNT) based on *Recommended Practice No. SNT-TC-1A*, ASNT SNT-TC-1A,[5] and *Personnel Qualification and Certification in Nondestructive Testing*, ANSI/ASNT CP-189.[6] These programs provide guidelines for the in-house certification of nondestructive examination technicians for each examination method used. Thus, these are in-house certification programs, except for the fact that the individual who oversees each program is certified directly by ASNT.

Other programs such as those offered by the International Organization for Standardization based on *Non-Destructive Testing—Qualification and Certification of Personnel,* ISO 9712,[7] and The Welding Institute's *Certification Scheme for Weldment Inspection Personnel (CSWIP),*[8] which has been adopted by AWS, are central certification programs for technicians. For more information on the qualification and certification of welding inspectors and nondestructive examination technicians, the reader is encouraged to consult "Certification and Qualification," Chapter 15 of this volume.

PHYSICAL, SOCIAL, AND INTELLECTUAL ABILITIES

The skills required of welding inspectors are acquired through both formal education and on-the-job training. The AWS Certified Welding Inspector (CWI) program defines many of these requirements, some of which are discussed below.[9]

Welding inspectors represent the manufacturers, purchasers, owners, and insurers of welded components. They might also represent public interest groups or government organizations that have no commercial involvement in the fabrication and marketing of welded components. Since the represented organization may subject the inspector to various pressures and influences, it is essential that he or she possess high ethical standards.[10]

1. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
2. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society.
3. American Welding Society (AWS) Qualification and Certification Committee, *Standard for AWS Certification of Welding Inspectors,* ANSI/AWS QC1, Miami: American Welding Society.
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6. American Society for Nondestructive Testing (ASNT), *Standard for Qualification and Certification of Nondestructive Testing Personnel,* ANSI/ASNT CP-189, Columbus, Ohio: American Society for Nondestructive Testing.
7. International Organization for Standardization (ISO), *Non-Destructive Testing—Qualification and Certification of Personnel,* ISO 9712, Geneva: Switzerland.
8. The *Certification Scheme for Welding and Inspection Personnel (CSWIP)*, a program administered by The Welding Institute (TWI) in the United Kingdom (UK), trains and certifies welding personnel in many disciplines, including visual inspection and nondestructive testing.
9. For further information, please refer to American Welding Society (AWS) Qualification and Certification Committee, *Standard for AWS Certification of Welding Inspectors,* ANSI/AWS QC1, Miami: American Welding Society.
10. This pressure can be minimized by management's efforts to support the inspection activity and minimize conflicts. Support is most effective when the inspection department reports directly to upper management. This reporting structure frees the inspectors from the pressures associated with the management of costs and production schedules.

With respect to physical abilities, welding inspectors must be sufficiently physically fit to observe welding and welding-related activities. This may require the ability to climb or to enter specific components. In all cases, welding inspection demands good eyesight, either natural or corrected. Some inspection tools also require adequate color vision for maximum effectiveness. Consequently, preliminary verification of visual acuity and other essential physical attributes is imperative for welding inspectors.

Inspectors serve as a link between departments with differing interests and often have to make unpopular decisions. The ability to form good working relationships with coworkers is a required social skill. Effective inspectors strive to earn the cooperation and respect of their coworkers by making impartial, consistent, and technically correct decisions. They are effective communicators—both orally and in writing—and they demonstrate a positive attitude toward the job.

The inspectors' familiarity with welding and welding-related activities should include knowledge of applicable welding processes and their associated welding consumables and preweld and postweld activities. The skills required in this area include the ability to interpret drawings; specifications; code requirements; and fabrication, testing, and examination procedures. They must understand testing methods and be able to perform and evaluate quality control tests. Inspectors must also maintain adequate records that document their findings, acceptances, and rejections. The ability to analyze these findings and recommend corrective actions is highly desirable.

JOB RESPONSIBILITIES

Inspectors must be familiar with the product; engineering drawings; specification requirements; manufacturing, testing, examination procedures; and the intended use of the product or component. This includes knowledge of the policies for the handling and disposition of any deviations from requirements or procedures. The writing and qualifying of welding procedure specifications are usually engineering functions, while the verification of welder and welding operator qualifications and the surveillance of performance records are inspection functions. Verification and surveillance require the inspector to compare qualification documents with the requirements of the applicable code or standard.

Codes and contractual documents can have different testing and acceptance criteria. Inspectors must be capable of correctly interpreting and applying this information. All decisions must be based on an in-depth understanding of these requirements. The performance and monitoring of mechanical, nondestructive, and proof-testing operations also requires knowledge of the corresponding requirements.

Inspection activities are not limited to the acceptance or rejection of the final product. Once a component has been completed, it may be difficult to evaluate its total quality and take corrective actions to ensure the desired quality. Consequently, certain inspection activities are appropriate both prior to and during fabrication, and still others are performed upon the completion of the fabrication process.

Inspection activities that are carried out prior to welding include the following:

1. Review and approval of welding procedures and welder qualifications,
2. Review of fabrication and examination plans,
3. Verification of the compliance of base metals with the applicable specifications,
4. Assessment of the adequacy of the welding equipment,
5. Verification of the compliance of welding consumables with the applicable specifications, and
6. Appraisal of joint designs and joint preparations for compliance with drawings.

Inspection activities performed during welding include the following:

1. Verification of proper fit, cleanliness, and environmental conditions;
2. Review of sequencing procedures for the control of distortion;
3. Verification of tack weld quality;
4. Validation of conformity to welding procedures and fabrication plans;
5. Verification of preheat and interpass temperatures;
6. Assurance of the proper control and handling of welding consumables;
7. Verification of welders' qualifications for specific operations;
8. Verification of the interpass and final cleaning; and
9. Performance of a visual examination and any required nondestructive examinations.

Inspection tasks conducted upon the completion of welding include the following:

1. Assurance of the product's conformity to drawings and specifications;
2. Verification of cleanliness and weld surface quality;
3. Oversight of nondestructive examination, proof, and if required, mechanical testing;
4. Oversight of repair activities;

5. Verification of the proper performance of postweld heat treatment, if required; and
6. Confirmation of adequate documentation of fabrication and inspection activities.

When these activities are applied to specific products and industries, the duties and requirements of welding inspectors are tailored to meet specific needs. At times, these details are left to the discretion of individual inspectors. In other cases, they are documented as part of a detailed quality assurance plan.

THE INSPECTION PLAN

An inspection plan is a documented description of the manner in which a given inspection activity will occur. Although the elements of the plan may be specified in a recognized industry standard, they are often dictated by the terms of the agreement reached between the customer and the supplier. While the inspection plan can be general in nature, it should address the degree of inspection and the required inspection steps as well as refer to particular specifications and procedures.

In some circumstances, the inspection of one hundred percent of the production is required. In other cases, sampling procedures are specified. The term *sampling* refers to the selection of a representative portion of the production for inspection or examination purposes. Statistically accurate conclusions can be drawn concerning an entire production lot by statistically analyzing the inspection results of a representative sample of the lot. When the sampling technique, sample size, and inspection method are not specified as part of a formal inspection procedure, these details should be reported with the inspection results.

SAMPLING METHODS

Sampling methodologies include partial sampling, which may be specified or random, and statistical sampling. Progressive examination may be used if the number of rejections exceeds the specified standards.

Partial Sampling

In the field of welding, partial sampling involves the inspection of a certain number of weldments, the total number of which is fewer than the total number in the lot or production run. The method of selection of the weldments to be inspected and the type of inspection should be prescribed in the sampling procedure. The rejection criteria and disposition for any substandard product found by the sampling inspection should also be specified in the procedure.

Specified Partial Sampling. A particular frequency or sequence of sample selection from the lot or production run may be prescribed on the drawing or in the specification. This sampling technique is known as *specified partial sampling*. An example of this type of sampling would be the selection of every fifth unit for inspection, starting with the fifth unit. Specified partial sampling is usually prescribed for fully automated operations to monitor process attributes.

Random Partial Sampling. When the units to be inspected are selected in a random manner, the method applied is referred to as *random partial sampling*. For example, one out of every five units from a production run may be inspected, with the specific selection made by the inspector in a random manner. Since it is not known which units are to be selected for inspection, equal care must be taken in the production of all units, likely resulting in improved product quality.

Progressive Examination. To improve the effectiveness of partial sampling, a progressive examination system may be employed. Progressive examination involves increasing the frequency of sampling when the percentage of rejections exceeds a specified value. For example, the inspection plan may specify that when a weld is rejected two additional welds in every group are to be inspected using the same inspection method.

Additional constraints may be imposed, such as the inspection of the welds produced by a particular welder or those made by the various welding operators at the same welding station. Selection criteria may also be based on a particular welding procedure used. It is important to note that during a progressive examination the welds must be selected randomly without notifying the welder or welding operator of the welds to be examined.

One result of invoking these criteria is that an increasingly large sample is required if the weld quality is low. In some circumstances, all completed welds in a lot may eventually require examination.

Statistical Sampling

Statistical sampling involves the use of one procedure to select probability samples and another to summarize the test results. In this way, specific inferences can be drawn, and the risks can be calculated by probability. However, this method of sampling may miss some defective products. The percentage of defective products accepted can be reduced by increasing the size of the sample. This method of sampling is used primarily for mass-produced products.

Statistical sampling functions most economically after statistical control has been attained. Control charts are the usual criteria for establishing statistical control of a process or operation. When it is desirable to take full advantage of the various plans for sampling, a statistical control chart must first be established to provide criteria for expected tolerances and data trends for inspected items.

Plans for statistical sampling should be designed to maximize the acceptance of good products and minimize the acceptance of poor products. It is impossible to estimate the quality of a production lot from a small sample. As a rule, the higher the percentage of production sampled, the lower the probability of error.

Selection of a Plan

When a plan is furnished in the procedure specification, the inspector need only follow the procedure. For the average welding job, inspection generally involves a combination of complete examination and random partial sampling. According to this technique, all welds are inspected visually. Random partial sampling is then applied using one or more of the other methods of nondestructive examination.

Complete inspection is performed when assurance is needed that weldments of the highest quality are used in critical service. One or more methods of nondestructive examination, along with visual examination, may be specified for critical joints.

NONDESTRUCTIVE EXAMINATION

The term *nondestructive examination (NDE)* is used to designate those inspection methods that allow materials to be examined without changing or destroying their usefulness. The terms *nondestructive testing (NDT)*, *nondestructive evaluation (NDE)*, and *nondestructive inspection (NDI)* are sometimes used interchangeably with the term *nondestructive examination (NDE)* and are generally considered synonymous. Nondestructive examination is performed on a weldment to verify that the weld quality meets the specification and to determine whether weld quality has degraded during service.

A number of different methods of nondestructive examination may be employed in welding inspection. Despite their differences, these methods have certain similarities. These include (1) a source of probing energy, (2) a test component with discontinuities capable of causing an alteration of the probing energy, (3) a device capable of detecting the differences in or the effects on the probing energy, and (4) a means of displaying the results of the test to allow for the interpretation and evaluation of discontinuities.

In order for a given NDE method to be successful, it must be carried out by a trained, qualified operator. The method must also incorporate a procedure for conducting the examinations, a means for reporting the results, and a standard by which to evaluate the results.

The forms of energy that can be used for the nondestructive examination of a particular weldment depend on the physical properties of the base and weld metals, the joint designs, and the accessibility of energy sources and detection devices. Thorough knowledge of each NDE method is needed for the proper selection of the proper methods for each application.

The NDE methods most commonly used for the inspection of weldments are:

1. Visual examination (VT),
2. Radiographic testing (RT),
3. Ultrasonic testing (UT),
4. Magnetic particle testing (MT),
5. Liquid penetrant testing (PT),
6. Electromagnetic testing (ET), and
7. Acoustic emission testing (AET).

These methods are discussed in detail below. Other NDE methods, such as thermographic and ferrite testing, exist for special types of examination; however, these are not discussed in this chapter. The considerations generally used in the selection of an NDE method for welds are summarized in Table 14.1.

VISUAL EXAMINATION

Visual examination (VT) is the nondestructive examination method that is used most extensively for weldments. This technique normally requires no special equipment. The principal requisite for this inspection activity is that the inspector have adequate vision. While visual examination is simple and relatively inexpensive, it provides valuable information about conformity to specifications.

Applications and Limitations

Visual examination is the primary evaluation method used in any quality control program. In addition to flaw detection, it can reveal signs of potential fabrication problems in subsequent operations and be incorporated

Table 14.1
Nondestructive Examination (NDE) Methods

Equipment	Applications	Advantages	Limitations
Visual Examination (VT)			
Magnifiers, projectors, color enhancement devices, other measurement equipment (e.g., rulers, micrometers, optical comparators, fillet weld gauges), and a light source.	Welds that have discontinuities on the surface.	Economical, expedient. Requires relatively little training and equipment for most applications.	Limited to external or surface conditions. Limited by the visual acuity of the examiner.
Radiographic Testing (RT)			
via Isotope			
Gamma ray sources, gamma ray camera projectors, film holders, films, lead screens, film processing equipment and solutions, film viewers, exposure facilities, and radiation monitoring equipment.	Most weld discontinuities, including incomplete joint penetration, cracking, porosity, inclusions, corrosion, and fit-up defects. Wall thickness dimensional evaluations.	Permanent record, which enables later review. Gamma sources may be positioned inside accessible objects for unusual technique radiographs. Source requires no electrical energy for the production of gamma rays.	Radiation is a safety hazard. Requires special facilities, or the areas where radiation will be used must be evacuated and monitored to control exposure levels and dosages to personnel. Sources (gamma) decay over their life and must be periodically replaced. Gamma sources have a constant output energy (wavelength) and cannot be adjusted. Gamma source and related licensing requirements are expensive. Not particularly sensitive to planar discontinuities such as incomplete fusion and cracks. Radiographic testing requires highly skilled operators and interpreters.
via X-Rays			
X-ray sources, electrical power source, and the same basic equipment as used with gamma sources.	Same applications as above.	Adjustable energy levels. Generally produces higher quality radiographs than gamma sources. Offers permanent record as with gamma radiography.	High initial cost of equipment. Not generally considered portable. Radiation hazard as with gamma sources. Skilled operators and interpreters required.
Ultrasonic Testing (UT)			
Instrument capable of exciting a piezoelectric transducer, thus generating ultrasonic energy within a test object, and a suitable electronic device capable of displaying the magnitudes of the reflected ultrasonic energy. Calibration standards and liquid couplant.	Most weld discontinuities including cracks, slag inclusions, incomplete joint penetration, incomplete fusion, lack of bond in brazing; thickness measurements.	Most sensitive to planar type discontinuities. Test results known immediately. Portable. Most ultrasonic flaw detectors operate from batteries as well as ac electrical input. High penetration ability.	Surface conditions must be suitable for coupling with transducer. Couplant required. Small welds, thin materials, and materials with large grains may be difficult to examine. Reference standards are required. Requires a highly skilled operator. The results of the examination are usually reported by the operator on a standard form; however, computer acquisition and processing are available, which can be stored for a permanent record.

(Continued)

Table 14.1 (Continued)
Nondestructive Examination (NDE) Methods

Equipment	Applications	Advantages	Limitations
Magnetic Particle Testing (MT)			
Prods, yokes, coils, and devices suitable for inducing magnetism into the test object; electrical power source; and fluorescent or visible magnetic powders. Some applications require special facilities and ultraviolet lights if fluorescent powders are used.	Most weld discontinuities open to the surface. Some large voids slightly subsurface. Most suitable for detection of cracks.	Relatively economical and expedient. Examination equipment is considered portable. Unlike penetrants, magnetic particle can detect some near-surface discontinuities. Indications may be preserved on transparent tape. Requires relatively little training.	Can only be applied to ferromagnetic materials. Parts must be clean before and after examination. Thick coatings require special techniques. Some applications require parts to be demagnetized after examination. Requires use of electrical power for most applications.
Liquid Penetrant Testing (PT)			
Fluorescent or visible penetrants, developers, cleaners, solvents, emulsifiers; suitable cleaning supplies; ultraviolet light source if fluorescent penetrants are used.	Weld discontinuities open to surface (e.g., cracks, porosity, incomplete joint penetration).	May be used on all nonporous materials. Portable, relatively inexpensive equipment. Expedient inspection results that are easily interpreted. Requires no electrical power except for light source. Indications may be further examined visually. Requires relatively little training.	Surface films such as coatings, scale, or smeared metal may mask or hide defects. Bleed-out from porous surfaces can also mask indications. Parts must be cleaned before and after examination.
Electromagnetic Testing (ET)			
An instrument capable of inducing electromagnetic fields within a test piece and sensing the resulting electrical currents with a suitable probe or detector; calibration standards.	Weld discontinuities open to the surface (e.g., cracks, porosity, and incomplete fusion); some subsurface inclusions; alloy content, heat treatment variations; and wall thickness of thin weldments.	Relatively expedient and low in cost. Automation possible for symmetrical parts. No couplant required. Probe need not be in direct contact with test piece.	Limited to electrically conductive materials. Shallow depth of penetration. Some indications may be masked by workpiece geometry due to sensitivity or permeability variations. Reference standards, some of which may be quite complex, are required.
Acoustic Emission Testing (AET)			
Emission sensors; amplifying electronics; signal processing electronics, including frequency gates and filters; and a suitable output system to evaluate the acoustic signal (audio monitor, visual monitor, counters, tape recorders, and an X-Y recorder).	Internal cracking in welds during cooling; crack initiation and growth.	Real-time and continuous surveillance inspection. May be applied remotely. Portability of inspection apparatus.	Requires the use of transducers coupled on the surface of the specimen. Workpiece must be in use or stressed. More ductile materials yield low amplitude emissions. Noise must be filtered out of the inspection system.

in process control programs. The prompt detection and correction of flaws or process deviations can result in significant cost savings. Visual examination during welding is the only nondestructive examination method that can assure that the mechanical properties in the weldment will be related to those determined during welding procedure qualification by ensuring that the welding procedure parameters (e.g., preheat, amperage, and so forth) are followed during welding.

Conscientious visual examination before, during, and after welding results in the detection of many defects that would otherwise be found later by more expensive nondestructive examination methods. The major limitation of visual examination as a quality control tool is that it detects only those conditions present at the surface of the weld or component being examined. Nonetheless, this method is still quite powerful when properly applied.

Required Equipment

Visual aids and gauges are sometimes used to facilitate the detection of discontinuities and to measure the size of welds and the discontinuities in welds. It is imperative that the welded joint be well illuminated to provide for good visibility. Auxiliary lighting may be needed. If the area to be inspected is not readily visible, the inspector may use mirrors, borescopes, flashlights, or other aids. Low-power magnifiers are also helpful in the detection of small discontinuities. However, care must be taken with magnifiers to avoid improper judgment of the size of discontinuities.

The inspection of welds usually incorporates a quantitative as well as qualitative assessment of the joint. Numerous standard measuring tools are available for the measurement of joint geometry and fit, weld size, weld reinforcement height, misalignment, and depth of undercut. Typical gauges used to measure welds are shown in Figure 14.1.

Certain situations require special inspection gauges to ensure that specifications are met. For example, indicators such as contact pyrometers and temperature-indicating crayons are used to verify that the preheat and interpass temperatures specified in the welding procedure are being implemented. The proper usage of visual aids and gauges requires that inspectors receive training in the application of these devices.

Inspection Activities and Procedures

For optimal results, the visual inspection activity must occur at various stages in the fabrication process—prior to the initiation of welding, during welding, and subsequent to the completion of welding operations. An effective program of visual examination that utilizes this approach usually results in the discovery of a large portion of defects that might be detected later using more costly nondestructive examination methods or missed if no other examination method is required. Consequently, visual examination programs are extremely cost effective when properly implemented.

Prewelding Inspection. Examination of the base metal prior to welding can reveal conditions that cause weld defects. Scabs, seams, scale, or other undesirable surface conditions can be identified by means of visual examination. Plate laminations can also be observed on cut edges. The base metal should be identified by type and grade, and the dimensions should be confirmed by measurement. Any necessary corrections should be made before the work proceeds.

Once the workpieces have been assembled for welding, the inspector should check the assembly for features that might affect the quality of the weld. Specifically, the inspector should examine the following for conformity to the applicable specifications:

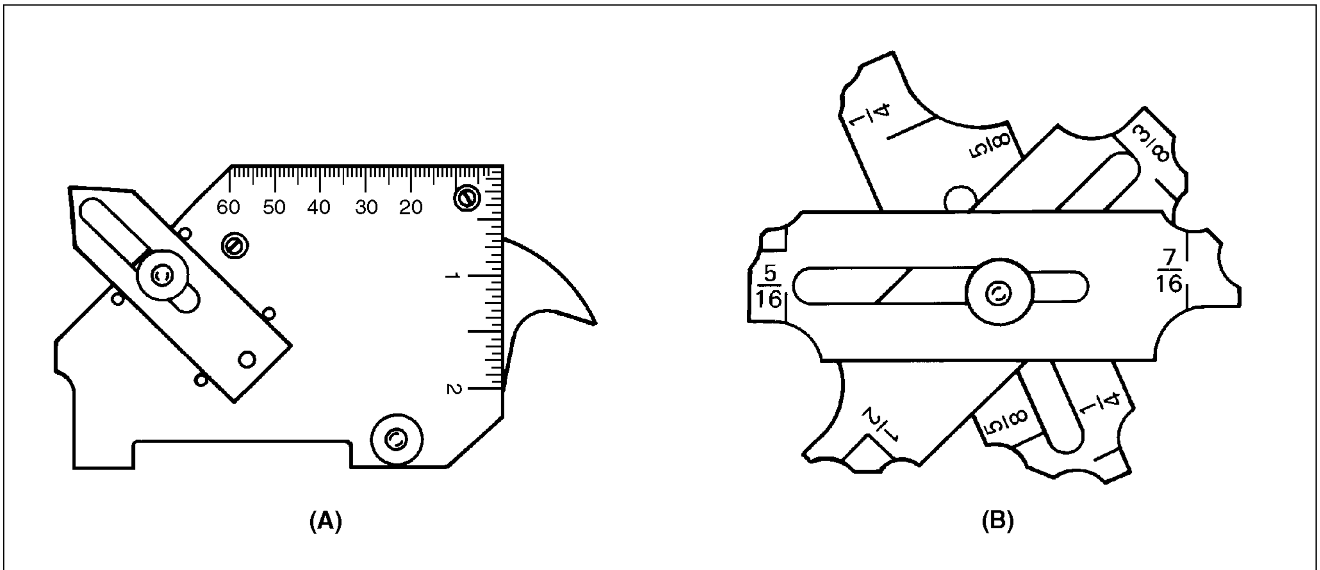


Figure 14.1—Typical Gauges for the Measurement of Weld Size and Shape: (A) Multipurpose Gauge and (B) Template-Type Fillet Weld Size Gauge

1. Groove preparation, surface preparation, dimensions, and cleanliness;
2. Clearance dimensions of backing strips, rings, or consumable inserts;
3. Alignment and fit of the pieces being welded;
4. Welding process and consumables;
5. Welding procedures and machine settings;
6. Specified preheat temperature; and
7. Tack weld quality.

Examination of the groove fit sometimes reveals irregularities that are within code limitations but may be of concern during subsequent steps. If these are of concern, they should be carefully monitored during subsequent inspections. For example, according to some codes, if the fit for a fillet weld exhibits a root opening when none is specified, the adjacent leg of the fillet weld must be increased by the amount of the root opening.

Inspection during Welding. During the course of welding, visual examination is the primary method of quality control. The aspects of fabrication that should be monitored at this time include the following:

1. Quality of the root pass and the succeeding weld layers,
2. Root condition prior to welding the opposite side,
3. Treatment of tack welds,
4. Proper preheat and interpass temperatures,
5. Sequence of weld passes for heat input or distortion control,
6. Interpass cleaning,
7. Conformance with the applicable welding procedure specifications, and
8. Filler metal control.

The most critical portion of all welds is the root pass, as many weld discontinuities are associated with the root area. Another critical root condition exists when second-side treatment is required of a double-welded joint. This includes the removal of slag and other irregularities by chipping, arc gouging, or grinding to sound metal. Thus, competent visual examination of both sides of the root pass may reveal a condition that would result in a discontinuity in the completed weld.

The root opening should be monitored as the welding of the root bead progresses. Special emphasis should be placed on the adequacy of tack welds, clamps, or spacers designed to maintain the specified root opening to assure complete joint penetration and alignment.

Inspection of successive layers of weld metal usually concentrates on bead shape and interpass cleaning. This is sometimes carried out with the assistance of quality standards (specimens). Examples of such standards are presented in Figure 14.2. These illustrate joints similar to those in manufacture in which portions of successive weld layers are visible. Each layer of the production weld may be compared with the corresponding layer of the quality standard.

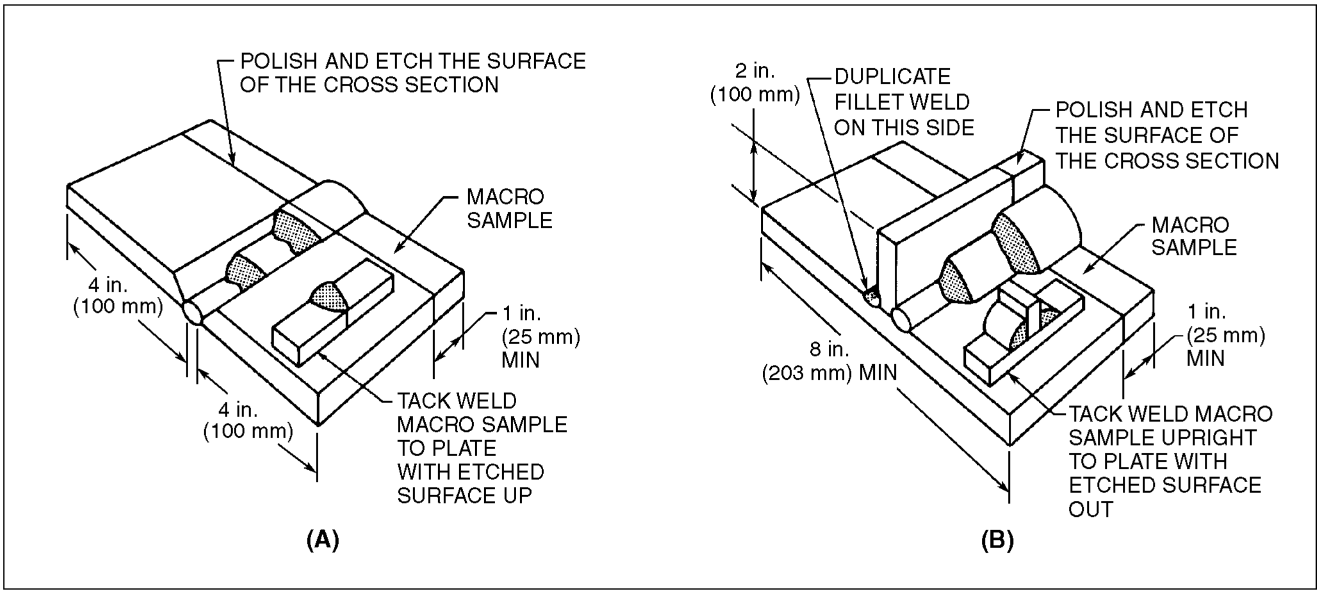


Figure 14.2—Quality Standards for Groove and Fillet Welds: (A) Groove Weld Standard and (B) Fillet Weld Standard

When preheat and interpass temperatures are specified, they should be monitored at the proper times with a suitable measuring device such as a temperature-indicating crayon or a pyrometer. The amount of heat input as well as the sequence and placement of each weld pass may be specified to maintain mechanical properties, limit distortion, or both.

To ensure weld quality as the work progresses, each weld layer should be scrutinized visually by the welder for surface irregularities and adequate interpass cleaning to avoid subsequent slag inclusions, porosity, or incomplete fusion.

Postweld Inspection. To permit the detection and accurate evaluation of discontinuities, the weld surface should be thoroughly cleaned of oxide and slag. The cleaning operation must be carried out carefully to avoid masking discontinuities from view. For example, if a chipping hammer is used to remove slag, the hammer marks could mask fine cracks. Shot blasting peens the surface of relatively soft weld metal and may hide discontinuities and should not be performed prior to visual examination without prior authorization.

Most codes and specifications describe the type and size of discontinuities that are acceptable. The following discontinuities, which are found on the surface of a completed weld, can often be detected by visual examination:

1. Cracks,
2. Undercut,
3. Overlap,
4. Exposed porosity and slag inclusions,
5. Unacceptable weld profile, and
6. Roughness of the weld faces.

Items that are monitored by visual examination after welding include the following:

1. Final weld appearance,
2. Dimensional accuracy,
3. Extent of welding,
4. Final weld size,
5. Amount of distortion, and
6. Postweld heat treatment.

The surface appearance of the weld should meet the requirements of the standard. Visual standards or sample weldments submitted by the fabricator and agreed to by the purchaser can be used as guides to appearance. When a good appearance is desirable, a smooth weld that is uniform in size is sometimes required if the weld is part of the exposed surface of the product or required for subsequent nondestructive examination.

The dimensional accuracy of weldments is determined by conventional measuring techniques. The conformity of the weld size and contour can be determined by the use of a suitable weld gauge. The size of a fillet weld in joints whose members are at right angles, or nearly so, is defined in terms of either its throat or leg dimensions, depending on the weld profile present. Thus, the size of a convex fillet weld is limited by the leg dimensions, while the size of a concave fillet weld depends on its throat dimension. The gauge used should be capable of determining if the weld size is within allowable limits and whether excessive concavity or convexity is present. Special gauges may be required to measure welds whose members form angles other than 90°.

For groove welds, the amount of weld reinforcement should be consistent with specified requirements. When the amount of reinforcement is not specified, the inspector may rely on judgment, guided by what is considered good welding practice. Surface appearance requirements differ widely.

A fabrication standard may permit limited amounts of undercut, undersize, and piping porosity. However, cracks, incomplete fusion, and unfilled craters are generally not acceptable. Undercut, overlap, and improper weld profile act as stress raisers under load, and cracks may develop at these locations under cyclic loading.

When a postweld heat treatment is specified, the operation should be monitored and documented by the inspector. Items of importance with respect to heat treatment include the following:

1. Area to be heated,
2. Heating and cooling rates,
3. Holding temperature and duration,
4. Temperature measurement and distribution, and
5. Equipment calibration and condition.

As a rule, care should be taken when judging the quality of a weld based on its visible appearance alone. Acceptable surface appearance does not guarantee quality, nor is it a reliable indication of subsurface weld integrity. However, the application of proper visual examination procedures prior to and during fabrication can increase product reliability as compared to that of products that have been subjected to final inspection only.

RADIOGRAPHIC EXAMINATION

Radiographic examination (RT) of weldments or brazements is a method that employs X-rays or gamma rays to penetrate an object and indicate any discontinuities by means of the resulting image on a recording or a viewing medium. This medium may be photographic film, sensitized paper, a fluorescent screen, or an electronic radiation detector.

The following are essential elements of radiographic testing:

1. A qualified radiographer who has been trained to perform the examination properly;
2. A source of penetrating radiation, such as an X-ray machine or a radioactive isotope;
3. A test object, such as a weldment, to be radiographed;
4. A recording or viewing device, usually photographic (X-ray) film enclosed in a light-tight holder;
5. Image quality indicators (IQIs) and other film identification markers for exposure verification and film identification;
6. A means of processing exposed film or operating other recording media;
7. A viewing unit such as a light box; and
8. A qualified, skilled radiographic film interpreter.

Radiographer Qualifications

The radiographer plays an essential role in successful radiographic testing. The relative positioning of the source and film with respect to the test object or weld affects the sharpness, density, and contrast of the radiograph. Many decisions must be made in choosing the procedure variables for specific examination conditions. The radiographer must also select the proper film type, intensifying screens, and filters.

In addition, proper safety procedures must be followed to prevent exposure to hazardous radiation in the work area. Applicable federal and local safety regulations must be followed during the handling and use of radiographic equipment.

Many fabrication codes and specifications require that radiographers be trained, examined, and certified to certain proficiency levels. The American Society for Nondestructive Testing (ASNT) publishes recommended guidelines for the certification of nondestructive examination personnel in *Recommended Practice No. SNT-TC-1A.*[11] ASNT also publishes *Personnel Qualification and Certification in Nondestructive Testing,* ANSI/ASNT CP-189,[12] which provides the minimum requirements for certification. Many codes and standards now specify this standard for the qualification of nondestructive examination personnel.

11. See Reference 5.
12. See Reference 6.

Procedures

When a test object or welded joint is exposed to penetrating radiation, some of the radiation is absorbed, some is scattered, and some is transmitted through the object to the recording medium. The amount of variation of radiation transmitted through the weld depends upon (1) the relative densities of the metal, (2) any inclusions, (3) through-thickness variations, and (4) the characteristics of the radiation itself. Nonmetallic inclusions, pores, cracks, and other discontinuities allow varying amounts of radiation to reach the recording or viewing medium. The variations in transmitted radiation produce optically contrasting areas on the recording medium.

Selecting a Source of Radiation. The type of radiation most suitable for welding inspection is that produced by high-voltage X-ray generation machines. The wavelength of the X-radiation is determined by the voltage applied to the elements in the X-ray tube. Higher voltages produce X-rays of shorter wavelength and increased intensity, resulting in greater penetrating capability. Typical applications of X-rays for various thicknesses of steel are presented in Table 14.2. With other metals, the penetrating ability of the X-rays generated by these machines may be greater or lesser, depending on the X-ray absorption properties of the metal. X-ray absorption properties are generally related to the density of the metal.

Gamma rays are emitted from the disintegrating nuclei of radioactive substances known as *radioisotopes*. Although the wavelengths of the radiation produced can be quite different, both X- and gamma radiation behave similarly for radiographic purposes. The three radioisotopes in common use are cobalt-60, cesium-137, and iridium-192, in order of decreasing energy level (and therefore penetrating ability). Cobalt-60 and iridum-192 are more widely used than cesium-137. The appropriate thickness limitations for steel when testing with these radioisotopes are presented in Table 14.3.

Table 14.2
Approximate Thickness Limitations of Steel for X-Rays

Maximum Voltage	Approximate Maximum Thickness	
kV	in.	mm
100	0.33	8
150	0.75	19
200	1	25
250	2	50
400	3	75
1000	5	125
2000	8	200

Table 14.3
Approximate Thickness Limitations of Steel for Radioisotopes

Radioisotope	Approximately Equivalent X-Ray Machine kV	Useful Thickness Range in.	mm
Iridium-92	800	0.5–2.5	12–65
Cesium-137	1000	0.5–3.5	12–90
Cobalt-60	2000	2–9	50–230

The advantages and limitations of each source of radiation are listed in Table 14.4. When selecting a source of radiation, the most significant consideration is usually its ability to produce an acceptable image quality. However, other important considerations include portability and cost.

Inasmuch as all radiation-producing sources are hazardous, special precautionary measures must be taken when entering or approaching a radiographic area. These are discussed in detail in the section "Safe Practices."

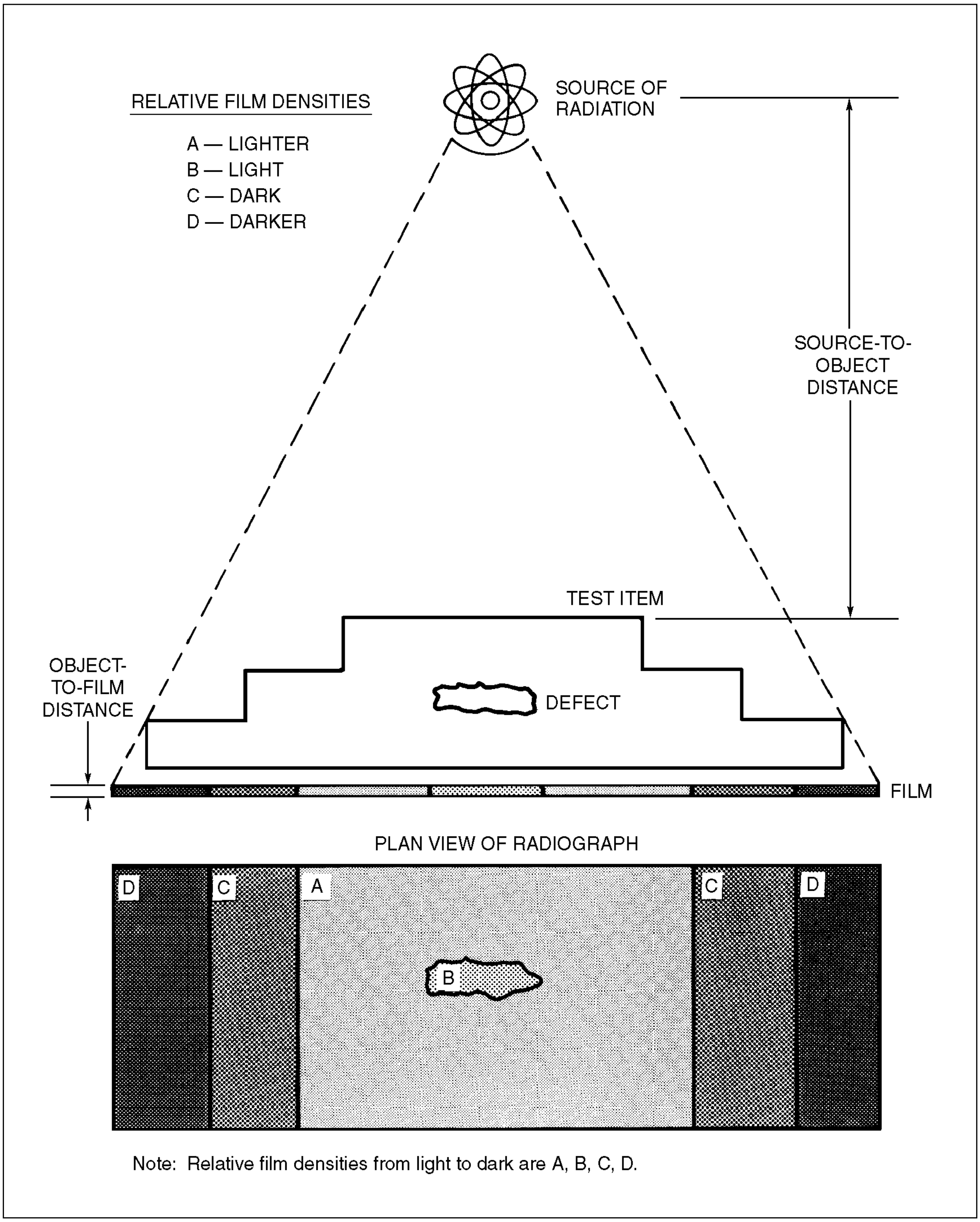
Test Object. Radiographic examination depends upon the differential absorption of the radiation as it passes through the test object. The rate of absorption is determined by (1) the penetrating power of the source, (2) the densities of the materials subject to radiation, and (3) the relative thickness of materials in the path of the radiation.

The various discontinuities found in welds absorb a different amount of radiation than the surrounding metal, depending on the density of the discontinuity and its thickness in the direction parallel to the radiation. Most discontinuities—slag inclusions, pores, and cracks, for example—are filled with material of relatively low density. They usually appear as dark regions on the recording medium as they have allowed more radiation to pass. Lighter regions indicate areas of greater thickness or density, such as weld reinforcement, spatter, and tungsten inclusions. These concepts are illustrated in Figure 14.3.

The thickest part of the test object allows the least amount of radiation to penetrate through to the film. Therefore, the area of the film marked "A" would appear the lightest on the film except in the location where discontinuity "B" is located. Assuming discontinuity "B" is a gas or slag pocket, it can be expected to absorb less radiation than the denser surrounding

Table 14.4
Advantages and Limitations of Radiation Sources

Radioisotopes	X-Ray Machines
Advantages	
Small and portable	Radiation can be shut off
No electric power required	Penetrating power (kV) is adjustable
No electrical hazards	Can be used on all materials
Rugged	Radiographs have good contrast and sensitivity
Can be used on all materials	
Low initial cost	
High penetrating power	
Access into small cavities	
Low maintenance costs	
Limitations	
Radiation emitted continuously by the isotope	High initial cost
Radiation hazard if improperly handled	Requires source of electrical power
Penetrating power cannot be adjusted	Equipment comparatively fragile
Radioisotope decays in strength, requiring continual adjustment of exposure times	Less portable recalibration and replacement
	Tube head usually large in size
Radiographic contrast is generally lower than that produced with X-rays	Electrical hazard from high voltage
Reduced radiographic sharpness	Radiation hazard during operation



Source: Adapted from American Welding Society (AWS) Committee on Methods of Inspection, 1980, *Welding Inspection*, Miami: American Welding Society, Figure 16.2.

Figure 14.3—Schematic Conceptualization of Radiographic Testing

metal, resulting in a darker image on the film (a tungsten inclusion in a gas tungsten arc weld appears as a lighter image on radiographic film). The film locations marked "C" and "D" are progressively darker because the thinner sections allow more radiation to penetrate and expose the film. The boundaries between the film densities would be wider than indicated in Figure 14.3, and the density would gradually change from one condition to the adjoining condition.

It is important to note that the film image is wider and larger than the test object. This phenomenon, which is termed *radiographic enlargement*, is caused by the divergence of the radiation from the source. The degree of enlargement increases with decreasing source-to-object distance and with increasing object-to-film distance.

Recording and Viewing Methods. The most commonly used recording medium is radiographic film made expressly for this purpose. Industrial radiographic film consists of a thin, transparent flexible plastic base on which a gelatin coating containing microscopic crystals of silver bromide has been deposited. The film may be coated with a gelatin emulsion on one or both sides. The emulsion is sensitive to both penetrating radiation and visible light; thus, it must be loaded into light-tight film cassettes (holders) in a darkroom. Radiographic films are classified according to speed, contrast, and grain size. Film selection depends on the nature of the inspection, the thickness and type of metal, required exposure time, and desired sensitivity.

Fluorescent screens or image amplifiers may be used to view the exposure results directly. Electronic devices can be used to enhance radiographic images or convert them to electrical signals for further processing, display, or recording.

Exposure Techniques. Radiographic film exposures are performed in a number of different arrangements. Typical arrangements for the radiographic testing of plate and pipe welds are shown in Figure 14.4. Figure 14.4(A) depicts a typical exposure arrangement for plate. The arrangement for pipe presented in 14.4(B) entails double-wall exposure and single-wall viewing with the source of the radiation contacting the outside of the pipe, while Figure 14.4(C) shows double-wall exposure and single-wall viewing with the source outside the pipe. Figure 14.4(D) illustrates single-wall exposure and single-wall viewing with the source outside the pipe, while Figure 14.4(E) demonstrates single-wall exposure and interpretation where the inside of the pipe is accessible. Figure 14.4(F) depicts single-wall exposure and single-wall panoramic viewing with the source inside the pipe.

The appropriate exposure arrangement depends upon the diameter and wall thickness of the plate or pipe. The optimal arrangement is chosen according to the following factors:

1. Best coverage of the weld,
2. Best image quality,
3. Shortest exposure time,
4. Optimum discovery of the discontinuities that are most likely to be present in a particular type of weld,
5. Use of either multiple exposures or one or more exposures at some angle to fully cover all areas of interest,
6. Radiation safety considerations, and
7. Whether single- or double-wall exposures should be used with a pipe weld, as illustrated in Figure 14.4.

Ensuring Radiographic Image Quality. When radiographic images are of high quality, they provide useful information about the internal soundness of the weld. Image quality is governed by radiographic contrast and definition. The variables that affect contrast and definition are shown in Figure 14.5.[13] These variables are controlled primarily by the radiographer and the film processor.

As a number of variables affect the image quality of a radiograph, some assurance is needed that adequate radiographic procedures have been implemented.[14] The tool used to provide proof of adequate exposure is the image quality indicator (IQI), sometimes referred to as a *penetrameter* or "penny." Two types of IQIs are used. One type consists of a piece of metal in a simple geometric shape with specifically sized holes. It has absorption characteristics similar to the weld under investigation. The other is a series of wires of different diameter encased in clear plastic. Typical IQIs are shown in Figure 14.6.

IQIs are manufactured in standard sizes, increments of thickness, and material groupings. Most codes and specifications organize commonly used metals and alloys into a minimum of five groups (absorption categories), ranging from light to heavy metals. An IQI of the appropriate grade should be used when radiographically examining a weldment made of an alloy in the group. When a weldment is to be radiographed, an IQI is selected according to the weld thickness. Lead numbers indicate the thickness or identification of the IQI being used.

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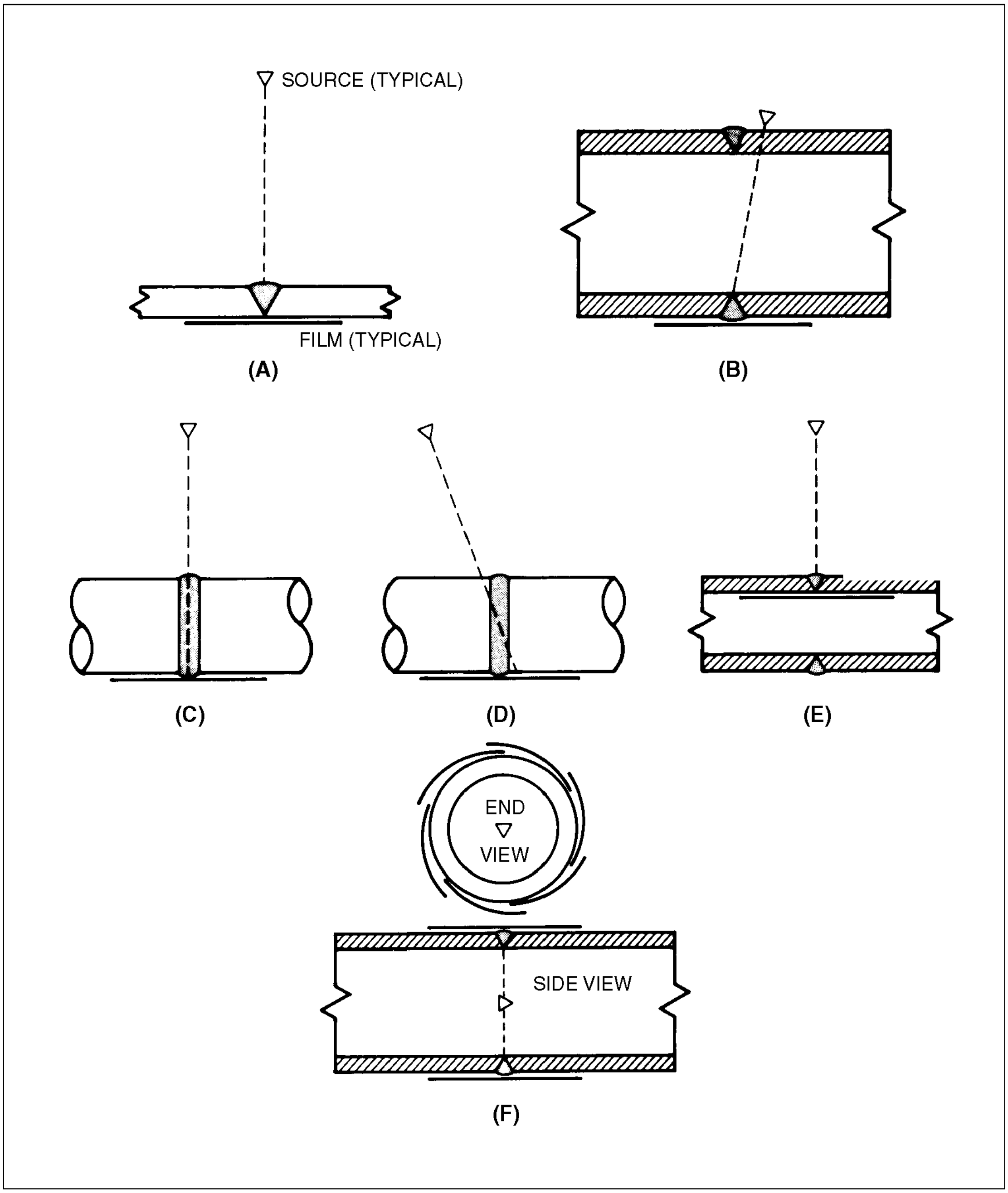
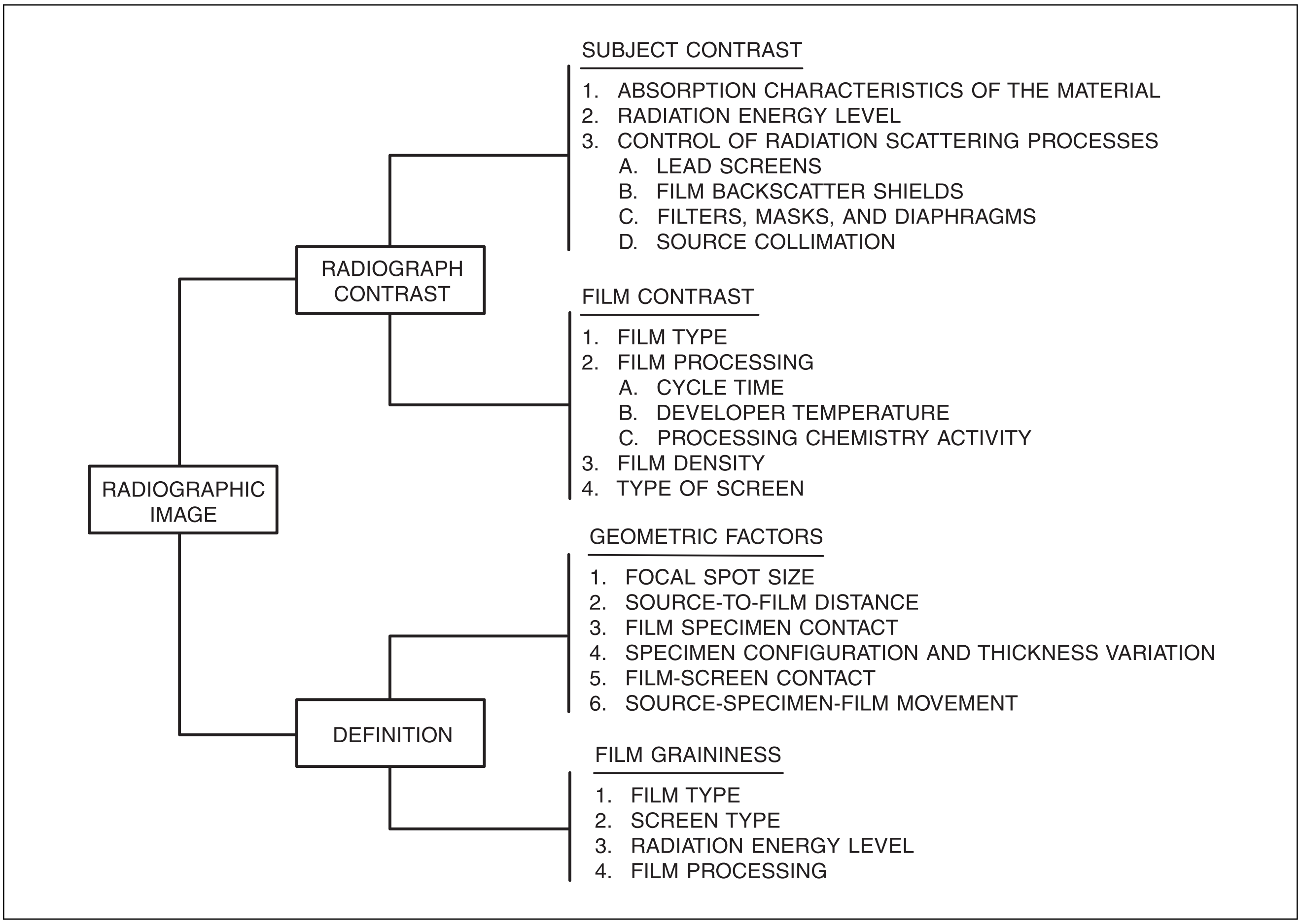
13. The variables that affect radiographic image quality are discussed in greater detail in American Welding Society (AWS) Committee on Methods of Inspection, 1980, *Welding Inspection,* Miami: American Welding Society.
14. For further information, refer to American Society for Testing and Materials Subcommittee E07.01, *Standard Guide for Radiographic Examination,* ASTM E 94, West Conshohocken, Pennsylvania: American Society for Testing and Materials.



Source: Adapted from American Welding Society (AWS) Committee on Methods of Inspection, 1980, *Welding Inspection*, Miami: American Welding Society, Figure 16.11.

Figure 14.4—Typical Radiographic Exposure Arrangements for Plate and Pipe Welds



Source: Adapted from AWS Committee on Methods of Inspection, 1980, *Welding Inspection*, Miami: American Welding Society, Figure 16.5.

Figure 14.5—Factors Affecting the Quality of Radiographic Images

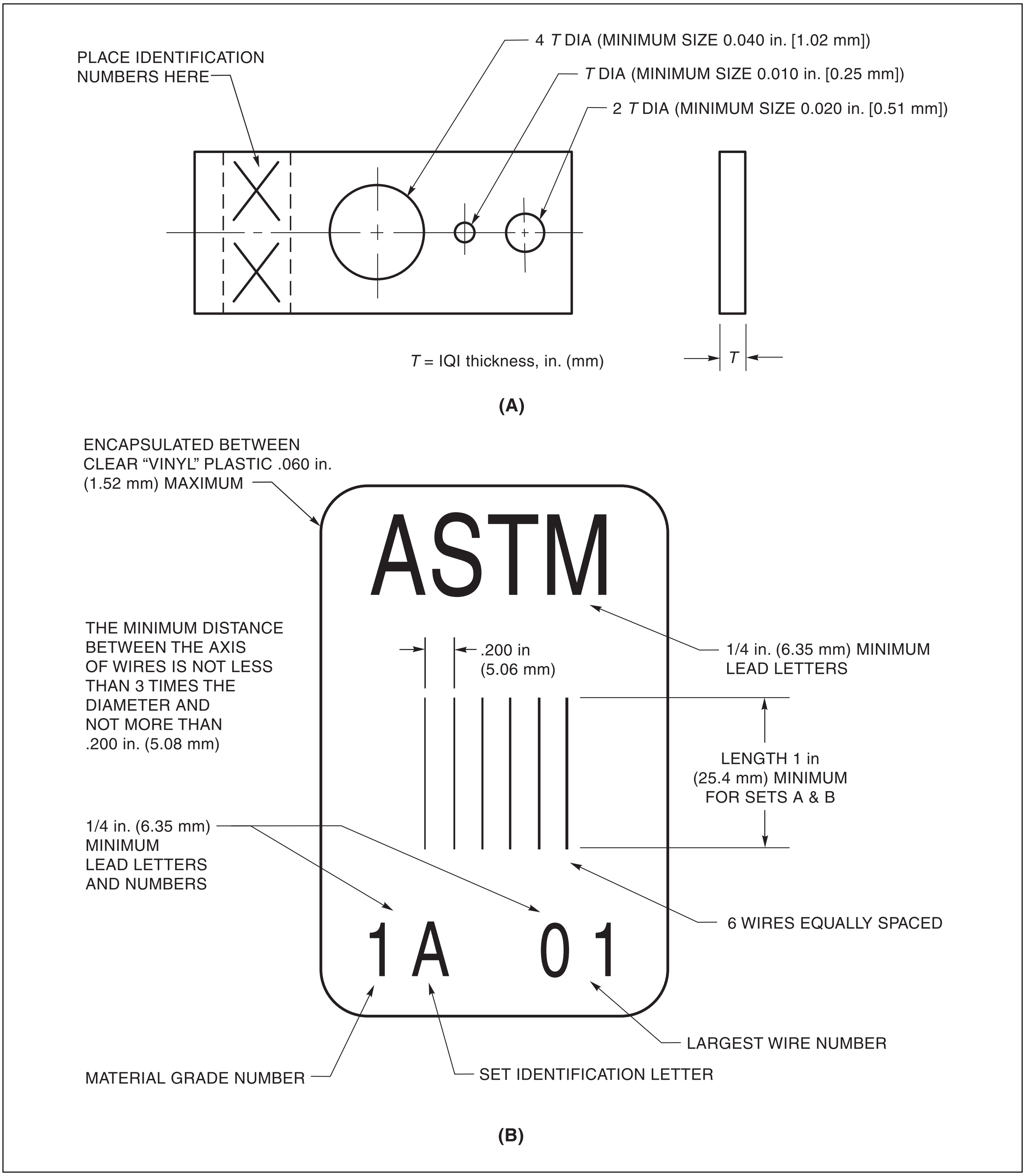
Conventional plaque-type IQIs contain three holes, the diameters of which vary in size as multiples of the thickness. Most specifications and codes call for 1T-, 2T-, and 4T-diameter holes, where "T" denotes the IQI thickness. When an exact IQI thickness is not available for a particular weld thickness, the next thinner IQI is normally used.

When the wire-type IQI is used, one of four sets of wires is selected according to the weld thickness. Whereas the conventional shim-type IQI is placed on the base metal adjacent to the weld toe, the wire type is placed directly on the weld face with the wires oriented perpendicular to the weld axis.

Most radiographic image quality requirements are expressed in terms of IQI thickness and desired hole size. For example, the requirement might be 2-2T level of sensitivity. The first "2" requires the IQI thickness to be 2% of the thickness of the specimens; the term "2T" requires that the hole having a diameter twice the IQI thickness must be visible on the radiograph. This image quality level is commonly specified for routine radiography. For more sensitive radiography, a sensitivity level of 1-2T or 1-1T could be required. More relaxed image quality requirements would imply sensitivities of 2-4T and 4-4T.

Most fabrication and inspection standards specify the exact IQI for a range of nominal base metal thicknesses. Tables 14.5 and 14.6 present the IQI requirements of *Structural Welding Code—Steel,* AWS D1.1:2000,[15] for plaque- and wire-type IQIs, respectively.

15. American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.



Source: Adapted from American Society for Testing and Materials (ASTM) Subcommittee E07.01, 1995, *Standard Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology*, ASTM E 1025-95, American Society for Testing and Materials, Figure 1; and American Society for Testing and Materials (ASTM) Subcommittee E07.01, 1997, *Standard Practice for Design, Manufacture, and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology*, ASTM E 747-97, Figure 1, respectively.

Figure 14.6—Typical IQI Designs: (A) Plaque or Hole Type (B) Wire Type

Table 14.5
Requirements for Plaque-Type Image Quality Indicator (IQI)

Nominal Material Thickness* Range	Nominal Material Thickness* Range	Source Side		Film Side†	
in.	mm	Designation	Essential Hole	Designation	Essential Hole
Up to 0.25 incl.	Up to 6 incl.	10	4T	7	4T
Over 0.25 to 0.375	Over 6 through 10	12	4T	10	4T
Over 0.375 to 0.50	Over 10 through 12	15	4T	12	4T
Over 0.50 to 0.625	Over 12 through 16	15	4T	12	4T
Over 0.625 to 0.75	Over 16 through 20	17	4T	15	4T
Over 0.75 to 0.875	Over 20 through 22	20	4T	17	4T
Over 0.875 to 1.00	Over 22 through 25	20	4T	17	4T
Over 1.0 to 1.25	Over 25 through 32	25	4T	20	4T
Over 1.25 to 1.50	Over 32 through 38	30	2T	25	2T
Over 1.50 to 2.00	Over 38 through 50	35	2T	30	2T
Over 2.00 to 2.50	Over 50 through 65	40	2T	35	2T
Over 2.50 to 3.00	Over 65 through 75	45	2T	40	2T
Over 3.00 to 4.00	Over 75 through 100	50	2T	45	2T
Over 4.00 to 6.00	Over 100 through 150	60	2T	50	2T
Over 6.00 to 8.00	Over 150 through 200	80	2T	60	2T

*Single-wall radiographic thickness (for tubulars).
†Applicable to tubular structures only.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Table 6.4.

Table 14.6
Requirements for Wire-Type Image Quality Indicator (IQI)

Nominal Material Thickness* Range	Nominal Material Thickness* Range	Source Side Maximum Wire Diameter		Film Side† Maximum Wire Diameter	
in.	mm	in.	mm	in.	mm
Up to 0.25 incl.	Up to 6 incl.	0.010	0.25	0.008	0.20
Over 0.25 to 0.375	Over 6 to 10	0.013	0.33	0.010	0.25
Over 0.375 to 0.625	Over 10 to 16	0.016	0.41	0.013	0.33
Over 0.625 to 0.75	Over 16 to 20	0.020	0.51	0.016	0.41
Over 0.75 to 1.50	Over 20 to 38	0.025	0.63	0.020	0.51
Over 1.50 to 2.00	Over 38 to 50	0.032	0.81	0.025	0.63
Over 2.00 to 2.50	Over 50 to 65	0.040	1.02	0.032	0.81
Over 2.50 to 4.00	Over 65 to 100	0.050	1.27	0.040	1.02
Over 4.00 to 6.00	Over 100 to 150	0.063	1.60	0.050	1.27
Over 6.00 to 8.00	Over 150 to 200	0.100	2.54	0.063	1.60

*Single-wall radiographic thickness (for tubulars).
†Applicable to tubular structures only.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Table 6.5.

Images produced by placing an IQI on the source side of a weld are less well defined than those produced by positioning the IQI on the film side. It is not always practical to place the IQI on the source side. When radiographing a circumferential weld in a long pipe section, for example, the pipe, although accessible on the inside for the source, is not accessible on the inside for accurate placement of the IQIs. In this case, a thinner IQI may be located on the film side of the weldment. If this is done, a lead letter "F" should be placed adjacent to the IQI to indicate its location on the film side (the applicable specifications should first be consulted to determine whether this is permissible).

The appearance of the IQI image on the radiograph indicates the quality of the radiographic technique. Even though a certain hole in an IQI may be visible on the radiograph, a discontinuity of the same approximate diameter and depth as the IQI may not be visible. IQI holes have sharp boundaries and abrupt changes in dimensions, whereas voids or discontinuities may have gradual changes in dimension and shape. IQIs are therefore not used to measure the size of discontinuities or the minimum detectable flaw size.

Radiographic identification markers made of lead alloy are usually in the form of a coded series of letters and numbers. The markers are placed on the test piece at marked locations adjacent to the welded joint during setup. When a welded joint is radiographed, a clear, distinct image of the identification markers should be produced. Identification markers must be properly located so that their projected images do not coincide with the images of any regions of interest in the weldment.

The view identification and the test specimen identification usually appear in coded form. The view identification is usually a simple code (such as A, B, C, or 1, 2, 3) that relates an inherent feature of the weldment or a specific location on the weldment to the view used. The location of the view markers is handwritten in chalk or crayon directly on the piece so that correlation of the radiographic image with the test piece itself can be made during the interpretation and evaluation of the radiograph. As a minimum requirement, the identification code for a weld must enable each radiograph to be traced to a particular test piece or section of a test piece. The pertinent data concerning weld and test specimen identification should also be recorded in a log opposite the corresponding identification number.

It is important to note that radiography becomes less sensitive as an inspection method as joint thickness increases. Thus, other nondestructive examination methods may be preferred for the inspection of welds in thick sections.

Film Processing. The processing of exposed radiographic film can often determine the success or failure of the radiographic examination method. In fact, radiographs are only as good as the developing process, which is essentially the same as that used for black and white photographic film. During film handling and processing, cleanliness and care are essential. Dust, oily residues, fingerprints, droplets of water, and rough handling can produce false indications or mask real ones.

Interpreting the Radiograph. The finished radiograph film is evaluated to determine (1) the quality of the exposure; (2) the type, number, and location of the discontinuities present; and (3) the absence of any unacceptable indications in the weldment. This task requires a skilled film interpreter who is familiar with the requirements of the applicable codes and specifications and able to determine radiographic quality.

The skilled interpreter also requires knowledge of weld and related discontinuities associated with various metals and alloys, methods of fabrication, and radiographic techniques. These skills are acquired through a combination of training and experience. Most codes require film interpreters to meet the requirements of *Recommended Practices No. SNT-TC-1A*[16] or *Standard for Qualification and Certification of Nondestructive Testing Personnel,* ANSI/ASNT CP-189.[17]

Radiographic film viewing equipment (e.g., a light box) must be located in an area with subdued lighting to reduce interfering glare. A masking arrangement should be provided so that only the film is illuminated and the viewer's eyes are shielded from the light. Variable-intensity lighting in the light box is usually desirable to accommodate film of various average densities.

The essential steps of radiograph interpretation are listed below:

1. Determine the accuracy of the identification of the radiograph,
2. Identify the weld joint design setup and the welding procedure,
3. Verify the radiographic setup and procedure,
4. Review the film under good viewing conditions (i.e., in a darkened room and with high-intensity backlighting in the viewing equipment),
5. Determine if any false or irrelevant indications are present on the film and retake the radiograph if necessary,
6. Identify any surface irregularities and verify their type and presence by visual or other nondestructive examination method,
7. Evaluate the acceptability of discontinuities as compared to code or specification requirements, and
8. Prepare the radiographic examination report.

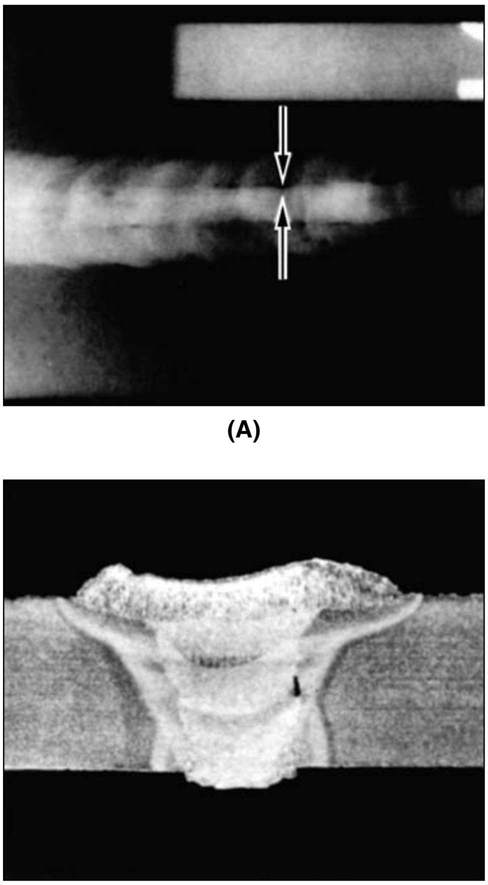
16. See Reference 5.
17. See Reference 6.

Identification of Weld Discontinuities

Radiographic examination produces a visible image of surface and subsurface weld discontinuities when these differ significantly in radiographic density from the base metal and have adequate thickness parallel to the direction of the radiation. However, this process fails to reveal very shallow discontinuities such as cracks, laps, and laminations that are not closely aligned with the radiation beam. Surface discontinuities are better identified by visual, penetrant, or magnetic particle examination unless the face and root of the weld are not accessible for examination.

Slag and Tungsten Inclusions. Slag inclusions generally produce images that appear as irregularly shaped dark areas with some width. Indications of slag inclusions are most frequently found at the edge of the weld bead or at weld interfaces, as illustrated in Figure 14.7. In contrast, tungsten inclusions appear as highly contrasted light areas or white spots, as the tungsten is denser than the surrounding material.

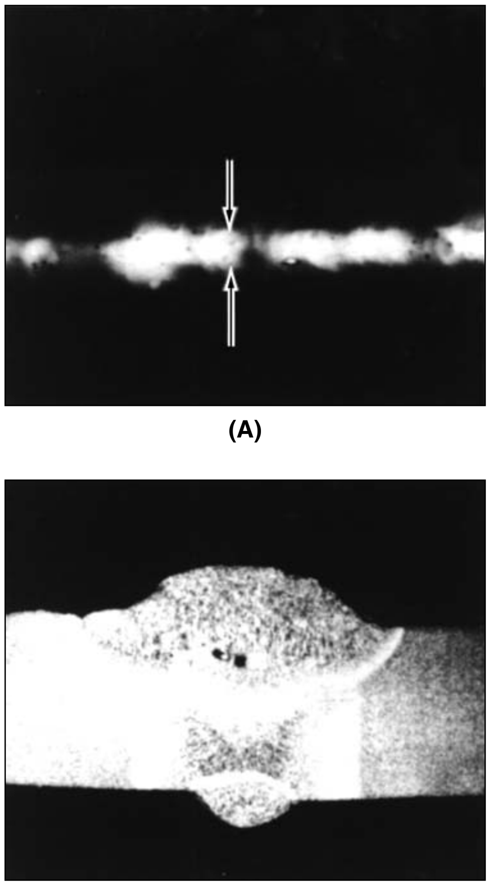
Porosity. Porosity indications appear as nearly round voids that are readily recognizable as dark spots whose radiographic contrast varies directly with diameter. These voids are normally found to be randomly dispersed, in clusters, or aligned along the centerline of the fusion zone. An example of porosity is presented in Figure 14.8. An image indicating elongated porosity appears as a dark rectangle if the long axis is perpendicular to the radiation and as concentric circles if the long axis is parallel to the beam.



(A)

(B)

Figure 14.7—Radiographic Image of Elongated Slag Between Beads: (A) Radiograph and (B) Metallographic Section



(A)

(B)

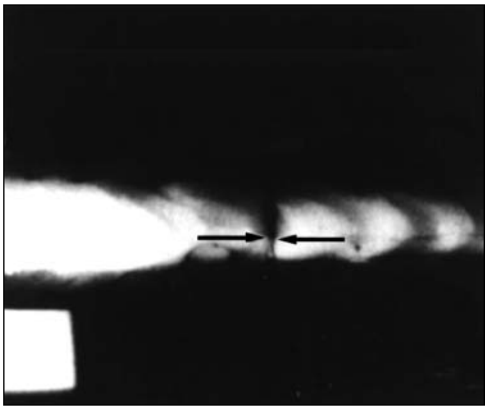
Figure 14.8—Radiographic Image of Weld Metal Porosity: (A) Radiograph and (B) Metallographic Section

Cracks. Cracks, which may be transverse or longitudinal, are typically located in the fusion zone or in the heat-affected zone of the base metal. Crack indications appear in radiographs as fine dark lines of considerable length, but without great width. Some fine crater cracks may also be detected. It is important to note, however, that cracks are often undetectable if they are very small or not aligned with the radiation beam. Examples of cracks in weldments are shown in Figures 14.9 and 14.10.

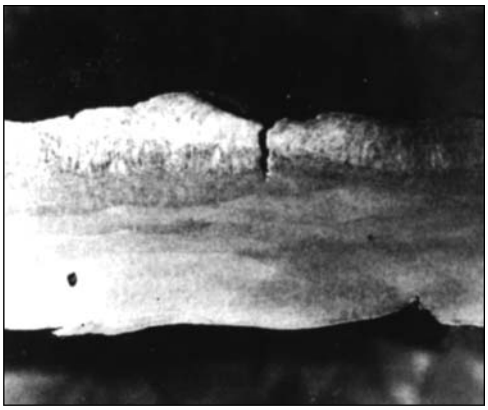
Incomplete Fusion. Images of incomplete fusion appear as elongated dark lines or bands. As these sometimes resemble the indications of cracks or inclusions, they are often interpreted as such and vice versa. Incomplete fusion occurs between the weld and base metal as well as between successive beads in multiple-pass welds. Due to its planar configuration, incomplete fusion may not be detected unless it is favorably oriented with respect to the radiation beam.

Incomplete Joint Penetration. Incomplete joint penetration is manifested on a radiograph as a very narrow dark line near the center of the weld, as shown in Figure 14.11. The narrowness can be a result of the drawing together of the plates during welding. Slag inclusions and gas holes are sometimes found in conjunction with incomplete joint penetration, in which case they cause the line to appear broad and irregular.

Undercut. As shown in Figure 14.12, undercut appears as a dark zone of varying width along the edge

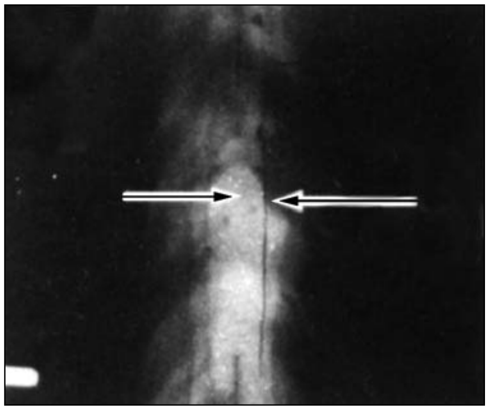


(A)

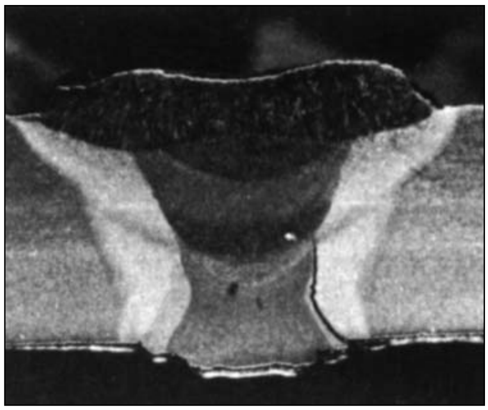


(B)

Figure 14.9—Radiographic Indication of a Transverse Crack in Weld: (A) Radiograph and (B) Longitudinal Metallographic Section

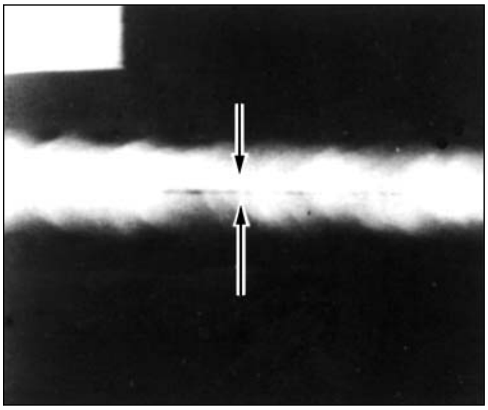


(A)

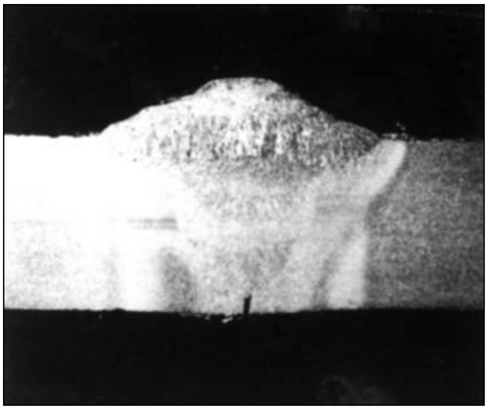


(B)

Figure 14.10—Radiographic Indication of a Longitudinal Crack in the Heat-Affected Zone: (A) Radiograph and (B) Longitudinal Metallographic Section

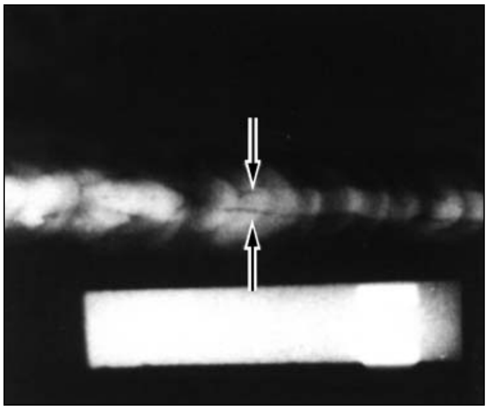


(A)

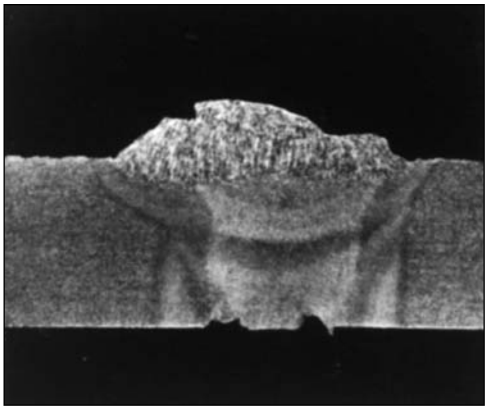


(B)

Figure 14.11—Radiographic Image of Incomplete Joint Penetration in a Weld: (A) Radiograph and (B) Metallographic Section



(A)



(B)

Figure 14.12—Radiographic Image of Undercut at the Root of a Weld: (A) Radiograph and (B) Metallographic Section

of the fusion zone. The darkness or density of the line is an indicator of the depth of the undercut.

Root Underfill. Root underfill, or the presence of a concave root surface, occurs only in joints that are welded from one side, such as pipe joints. It appears on the radiograph as a region that is darker than the base metal and runs along the center of the weld.

Safe Practices in Radiographic Examination

Federal, state, and local governments issue licenses for the operation of radiographic facilities. The federal licensing program is concerned primarily with companies that use radioactive isotopes as sources. In most localities, state and local agencies exercise similar regulatory prerogatives. Although local regulations vary in the degree and type of protection afforded, certain general principles apply to all. Most importantly, the amount of radiation that is allowed to escape from the area over which the licensee has direct and exclusive control is limited to an amount that is safe for continuous exposure.

To become licensed under any of these programs, a facility or operator must demonstrate that certain minimum requirements have been met to protect both operating personnel and the public from excessive levels of radiation.

Radiation Monitoring. Excessive exposure to radiation has the potential to cause injury, illness, or death. Therefore, adherence to safe practices during radiographic examination is critical. A radiation safety program must be developed and maintained to ensure that the facility housing the operation and all personnel subject to radiation exposure are monitored.

Facility monitoring is generally accomplished by taking periodic readings of radiation leakage during the operation of each source under various conditions. Calibrated instruments are used to measure radiation dose rates at various points within the restricted area and around the perimeter of the restricted area. Interlocks and alarms are often required to guard against the inadvertent leakage of large amounts of radiation from a shielded work area. An interlock disconnects power to an X-ray tube if an access door is opened or prevents any door from being opened if the unit is turned on. Alarms are connected to a separate power source and activate visible or audible signals, or both, whenever the radiation level exceeds a preset value.

All personnel within the restricted area must be monitored to ensure that they are not exposed to excessive amounts of radiation. Devices such as pocket dosimeters, which provide direct or remote readings, and film badges are the usual means of monitoring. Both are often worn by persons in the restricted area.

Access Control. Permanent radiology facilities are usually separated from unrestricted areas by shielded walls. Nonetheless, access barriers may consist merely of ropes or sawhorses, particularly during on-site radiographic examination. In such instances, the entire perimeter around the work area must remain under continual surveillance by radiographic personnel.

Signs that carry a symbol designated by the U.S. government must be posted around any radiation area. The posting of these signs helps to inform casual bystanders of the potential hazard but should never be assumed to prevent unauthorized entry into the hazard zone. In fact, no interlock, radiation alarm, or other safety device should be considered a substitute for constant vigilance on the part of radiographic personnel.

Advantages and Limitations

The chief advantage of radiographic examination is its capacity to detect subsurface discontinuities in all common engineering materials. Also advantageous is the fact that, if properly processed and stored, the film upon which images are recorded serves as a permanent record of examination results.

The safety hazard posed to personnel by excessive exposure to radiation constitutes its principal disadvantage. The costs incurred in capital expenditures and the specialized training required to ensure safe testing conditions and competent test performance and interpretation are also a limitation of this method. Moreover, radiographic examination may fail to detect critical flaws unless the source of radiation is preferentially positioned in relation to the direction of the discontinuity.

ULTRASONIC EXAMINATION

Ultrasonic examination (UT) is a nondestructive examination method in which beams of high-frequency sound waves are introduced into a test object to detect and locate surface and internal discontinuities. A sound beam is directed into the object on a predictable path. The beam is reflected at interfaces or other interruptions in material continuity. The reflected beam is then detected and analyzed to define the presence and location of discontinuities.

The detection and evaluation of discontinuities is possible because (1) the velocity of sound through a given material is nearly constant, making distance measurements possible and (2) the amplitude of a reflected sound pulse can be related to the size of the reflector.

Applications

Ultrasonic examination is used to detect cracks, laminations, shrinkage cavities, pores, slag inclusions, incomplete fusion or bonding, incomplete joint penetration, and essentially all discontinuities in weldments and brazements. It is also employed to measure the thickness of components and inspect the base material for laminations and other manufacturing discontinuities. Using the proper techniques, the approximate position, depth, and, in some cases, size of the discontinuity can be determined with good precision.

Theory

Sound passes through most metals in a fairly well-defined beam. The sound beam initially has a cross section approximately the size of the transducer element. It propagates with slight divergence in a fairly straight line. As the sound beam travels through the material, some attenuation or decrease in energy occurs. The beam continues to propagate until it reaches a boundary, or interface, within the object being tested. Either partial or complete reflection of the sound beam takes place at a boundary.

The behavior of sound at UT frequencies resembles that of visible light in the following ways:

1. Divergence of the beam can be controlled by focusing, like a laser beam;
2. The beam reflects predictably from surfaces of different densities, as light reflects from a mirror; and
3. The beam refracts at an interface between materials of different density, as light does as it passes through the atmosphere.

On the other hand, the behavior of sound at the frequencies used in ultrasonic examination differs from that of light in that different vibrational modes and velocities can occur in the same medium.

Wave Forms. Three basic modes of propagating sound through metals are used in ultrasonic examination. They involve the use of longitudinal, transverse, and surface waveforms. In these modes, waves are propagated by the displacement of successive atoms or molecules in the metal. However, the surface waves are limited to propagation along a solid-gas interface rather than through the solid material.

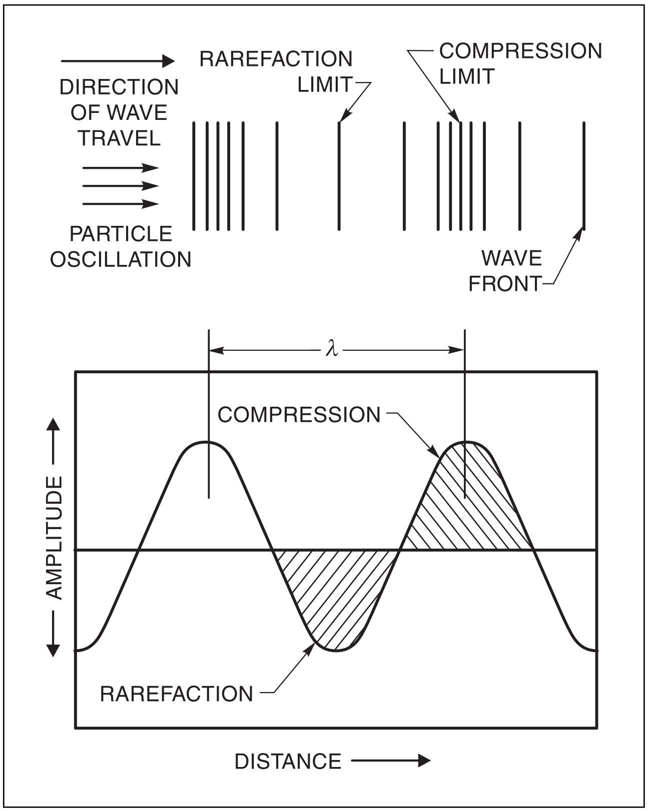
Longitudinal waves, sometimes termed *straight* or *compressional waves*, represent the simplest wave mode. This waveform exists when the motions of the particles are parallel to the direction of sound beam propagation, as shown in Figure 14.13. Longitudinal waves have a relatively high velocity and a relatively short wavelength. As a result, the energy can be focused into a sharp beam with a minimum of divergence. Longitudinal waves are readily propagated in water. Longitudinal-wave ultrasound is generally used for the detection of inclusions and lamellar-type discontinuities in base metal.

In the transverse, or shear, wave mode, the principal particle motion is perpendicular to the direction of the propagation of the sound beam, as shown in Figure 14.14. The velocity of these waves is approximately half that of longitudinal waves. One advantage of transverse waves is lower velocities that allow for easier electronic timing and a greater sensitivity to small indications. On the other hand, these waves are more easily dispersed and cannot be propagated in a liquid medium (water).

Shear waves, generated by transmitting longitudinal waves into the workpiece at an angle, are the most valuable in the detection of weld discontinuities because of their ability to furnish three-dimensional coordinates for discontinuity locations, orientations, and characteristics. The sensitivity of shear waves is also approximately double that of longitudinal waves for the same frequency and search unit size. However, the zones in the base metal adjacent to a weld should first be tested with longitudinal waves to ensure that the base metal does not contain discontinuities that would interfere with shear wave evaluation of the weld.

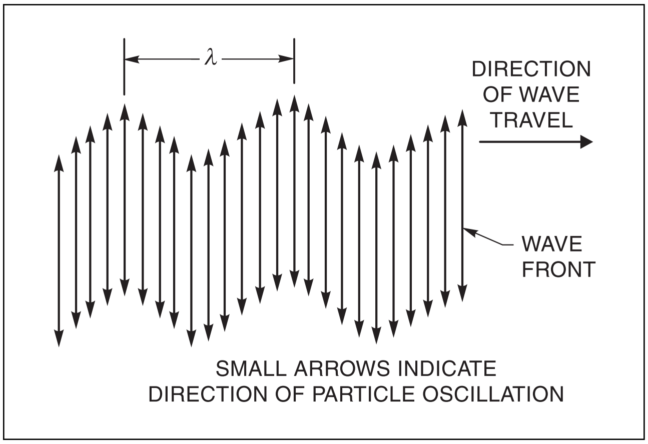
In the third mode, which involves the use of surface or Rayleigh waves, ultrasonic waves are propagated along the surface of the metal, similar to waves on the surface of water. As these surface waves have little movement below the surface of a metal, these waves have only a limited application for the examination of welded and brazed joints.

Wave Frequencies. The sound wave frequencies used in weld inspection are typically between 1 megahertz (MHz) and 6 MHz. Most weld testing is performed at 2.25 MHz. Higher frequencies (5 MHz, for example)



Source: Adapted from Bar-Cohen, Y., and A. Mal, 1989, Ultrasonic Inspection, in *Nondestructive Evaluation and Quality Control*, Vol. 17 of *ASM Handbook*, 9th ed., Metals Park, Ohio: ASM International, Figure 1.

Figure 14.13—Direction of Atomic Vibration in Longitudinal Waves



Source: Adapted from Bar-Cohen, Y., and A. Mal, 1989, Ultrasonic Inspection, in *Nondestructive Evaluation and Quality Control*, Vol. 17 of *ASM Handbook*, 9th ed., Metals Park, Ohio: ASM International, Figure 2.

Figure 14.14—Direction of Atomic Vibration in Transverse (Shear) Waves

produce small, sharp sound beams that are useful in locating and evaluating discontinuities in thin-walled weldments.

Operator Qualifications

The performance of ultrasonic examination requires more training and experience than the other nondestructive examination methods, with the possible exception of radiographic testing. The operating technician is the key to the success of the method. As many critical variables are controlled by the operating technician, the accuracy of an ultrasonic examination depends to a great extent on knowledge and ability of the operator. For this reason, most standards require ultrasonic technicians to meet the guidelines presented in *Recommended Practice No. SNT-TC-1A*[18] or *Personnel Qualification and Certification in Nondestructive Testing*, ANSI/ASNT CP-189.[19] Experience in welding and other nondestructive examination methods is also helpful.

Equipment

Most ultrasonic examination systems use the following basic components:

1. An electronic signal generator (pulser) that produces bursts of alternating voltage,
2. A sending transducer that emits a beam of ultrasonic waves when alternating voltage is applied,
3. A couplant to transmit the ultrasonic energy from the transducer to the test piece and vice versa,
4. A receiving transducer to convert the sound waves to alternating voltage (this transducer may be the same as the sending transducer),
5. An electronic device to amplify and demodulate or otherwise change the signal from the receiving transducer,
6. A display or indicating device to characterize or record the output from the test piece,
7. An electronic timer to control the operation, and
8. A source of electrical power.

A typical ultrasonic examination system is depicted schematically in Figure 14.15.

Equipment operated in a pulse-echo method (see below) with video presentation is most commonly used for the hand scanning of welds. The pulse-echo equipment produces repeated bursts of high-frequency sound with a time interval between bursts to receive signals from the test piece and any discontinuities in the weld or base metal. The pulse rate is usually between 100 and 5000 pulses per second.

18. See Reference 5.
19. See Reference 6.

In the A-scan video presentation, the time base line is located horizontally along the bottom of a cathode ray tube (CRT) screen. A vertical initial pulse indication is displayed at the left end of the base line. In this presentation, the time lapse between the initial pulse and the received echoes is shown on the horizontal axis (see Figure 14.15), and the relative amplitude of the received echoes is displaced vertically. Horizontal spacing is proportional to the distance sound has traveled in the test specimen, while signal heights are indicative of the relative sizes of reflectors. The screen is usually graduated in both the horizontal and vertical directions to facilitate the measurement of pulse displays.

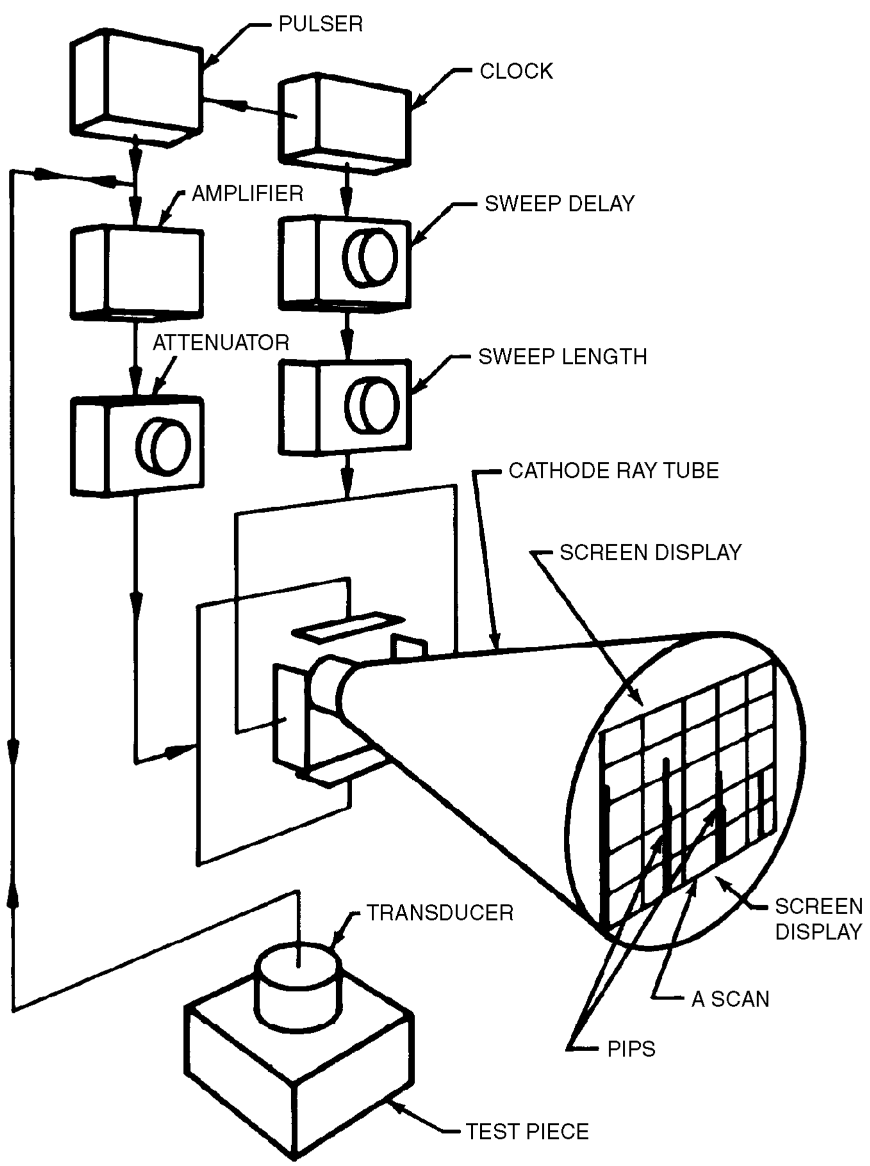
A search unit, consisting of a holder and a transducer, is used to direct a sound beam into the test object. The transducer element is usually a piezoelectric crystalline substance. When excited with high-frequency electrical energy, the transducer produces mechanical vibrations at a natural frequency.

A transducer can also receive physical vibrations and transform them into low-energy electrical impulses. In the pulse-echo mode, the ultrasonic unit senses reflected impulses, amplifies them, and presents them as spikes called *echoes* on the CRT screen. The horizontal location of a reflector echo on the screen is proportional to the distance the sound has traveled in the test specimen because of the relationship between sound velocity and distance, i.e., velocity equals distance divided by time. This makes it possible to determine the location of reflectors by using horizontal screen graduations as a distance-measuring ruler.

Procedures

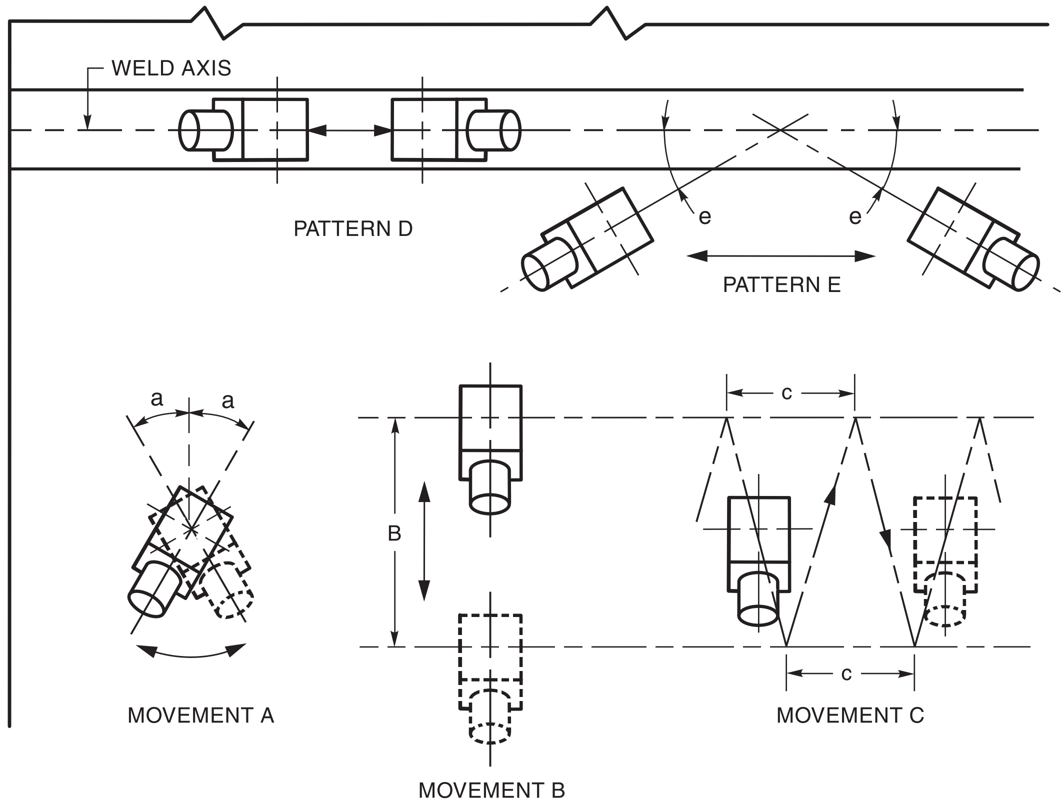
Ultrasonic examination should be performed in accordance with a written procedure. Most specifications list the requirements for the contents of a written procedure. Most ultrasonic examinations of welds are performed in accordance with a specific code or procedure. An example of such a procedure is that contained in *Structural Welding Code—Steel*, AWS D1.1:2000,[20] for the examination of groove welds in steel structures. *Standard Practice for Ultrasonic Contact Examination of Weldments*, ASTM E 164,[21] addresses the examination of specific weld configurations in wrought ferrous and aluminum alloys to detect weld discontinuities. Recommended procedures for the examination of butt, corner, and T-welds are provided for weld thicknesses from 0.5 in. to 8 in. (12 mm to 204 mm). Procedures for calibrating the equipment and appropriate calibration blocks are also included.

20. See Reference 15.
21. American Society for Testing and Materials (ASTM) Subcommittee E07.06, *Standard Practice for Ultrasonic Contact Examination of Weldments,* ASTM E 164, West Conshohocken, Pennsylvania: American Society for Testing and Materials.



Source: AWS Committee on Methods of Inspection, 1980, *Welding Inspection*, Miami: American Welding Society, Figure 16.3.

Figure 14.15—Schematic Representation of a Pulse-Echo Flaw Detector



Notes:
1. Testing patterns are all symmetrical around the weld axis with the exception of Pattern D, which is conducted directly over the weld axis.
2. Testing from both sides of the weld axis is to be made wherever mechanically possible.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 6.24.

Figure 14.16—Typical Search Patterns Used in Ultrasonic Examination

Other ASTM standards cover examination procedures utilizing various ultrasonic examination methods for the inspection of pipe and tubing. Procedures for the ultrasonic testing of boiler and pressure vessel components are provided in Section 5, *Nondestructive Examination*, of the ASME *Boiler and Pressure Vessel Code.*[22] In addition, Section 11, *Inservice Inspection Requirements for Nuclear Power Plants,* of the same code[23] provides methods for locating, sizing, and evaluating discontinuities for continuing service life and fracture mechanics analysis.

To examine a welded joint properly using ultrasonic examination, the search unit must be manipulated in specific patterns to cover the through-thickness and length of the joint adequately. In most cases, the joint must be scanned from two or more directions to ensure that the beam intercepts any discontinuities that exist. Typical search patterns for the examination of groove welds are shown in Figure 14.16. Similar procedures for butt, corner, and T-joints are illustrated in *Standard*

22. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, *Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers.
23. See Reference 22.

Practice for Ultrasonic Contact Examination of Weldments, ASTM E 164.[24]

Coupling. A liquid couplant is generally used to allow the transmission of ultrasonic waves into the test object. In addition to commercially available gel couplants marketed for this sole purpose, some of the more common couplants are water, light oil, glycerin, and cellulose gum powder mixed with water. A weldment must be smooth and flat to allow intimate coupling of the transducer with the test specimen. Weld spatter, slag, and other surface irregularities should be removed. Depending on the examination technique, removal of the weld reinforcement may also be necessary.

Couplants and the solvents used to remove them can be detrimental to repair welding or subsequent operations as well as the weld and the base metal. However, couplants that minimize these problems are available.

Calibration. Ultrasonic examination is essentially a comparative evaluation. The horizontal (time) and the vertical (amplitude) dimensions on the CRT screen of the evaluation unit are a measure of distance and size, respectively. A zero starting point must be established for these variables, and an ultrasonic unit must be calibrated to some basic standard before use.

Various configurations of blocks are used to assist in the calibration of the equipment. Standard calibration blocks are shown in *Standard Practice for Ultrasonic Contact Examination of Weldments,* ASTM E 164.[25] In these test blocks, notches substitute for surface-breaking cracks, while side-drilled holes substitute for slag inclusions and internal cracks, and angulated flat-bottomed holes represent small areas of incomplete fusion. The material from which the test block is made must be similar in acoustic properties to those of the metal being tested.

The International Institute of Welding (IIW) calibration block is widely used as a calibration block for the ultrasonic examination of steel welds. This and other test blocks are used to calibrate instruments for sensitivity, resolution, linearity, angle of sound propagation, and distance and gain calibrations.

Evaluation of Weld Discontinuities

The reliability of ultrasonic examination depends greatly upon the interpretive ability of the UT technician. With the proper use of inspection techniques, significant information about discontinuities can be obtained from the signal response and display on the CRT screen.

Six basic items of information that describe weld discontinuities are made available through ultrasonic examination, depending upon the sensitivity of the test. These are as follows:

1. The amplitude of the returned signal relative to that of a reference reflector is an approximate measure of the reflecting area (see Figure 14.17);
2. Length of a discontinuity is determined by search unit travel in the length-wise direction (see Figure 14.18);
3. Location of a discontinuity in the weld cross section can be estimated (see Figure 14.19);
4. Orientation, and to some degree, the shape of the discontinuity can be determined by comparing signal sizes that are derived from examining from different directions (see Figure 14.20);
5. Reflected pulse shape and sharpness can be used as an indicator of discontinuity type (see Figure 14.21); and
6. Height of the discontinuity within the weld can be estimated by the coordination of the travel distance of the search unit to and from the weld with the rise and fall of the signal (see Figure 14.22).

These six items of information can be used in the following manner. The first two items, the returned signal size and length, are used as a basis for accepting or rejecting a single discontinuity in a weld. The third item, the location of the discontinuity within the cross section of the weld, is useful information when making a repair or evaluating a discontinuity for its severity. Each of these first three items is essential in the proper inspection of welding for acceptance or rejection. The latter three items of information, namely orientation, pulse shape, and dynamic envelope (i.e., how the signal size and shape changes with transducer movement), are used to enhance the accuracy of the evaluation of the nature of the discontinuity. This information is of value in determining if the welding procedures are under control and whether the component can continue in service without repair.

Reporting Process

The careful tabulation of information on the report form is necessary for a meaningful examination. It is especially important for the UT technician to fill out the appropriate report form accurately and completely as it must include dimensional information that is necessary for the accurate location of defects for subsequent repairs. The welding inspector should be familiar with the kinds of data that must be recorded and evaluated so that a satisfactory determination of weld acceptability can be obtained.

24. See Reference 21.
25. See Reference 21.

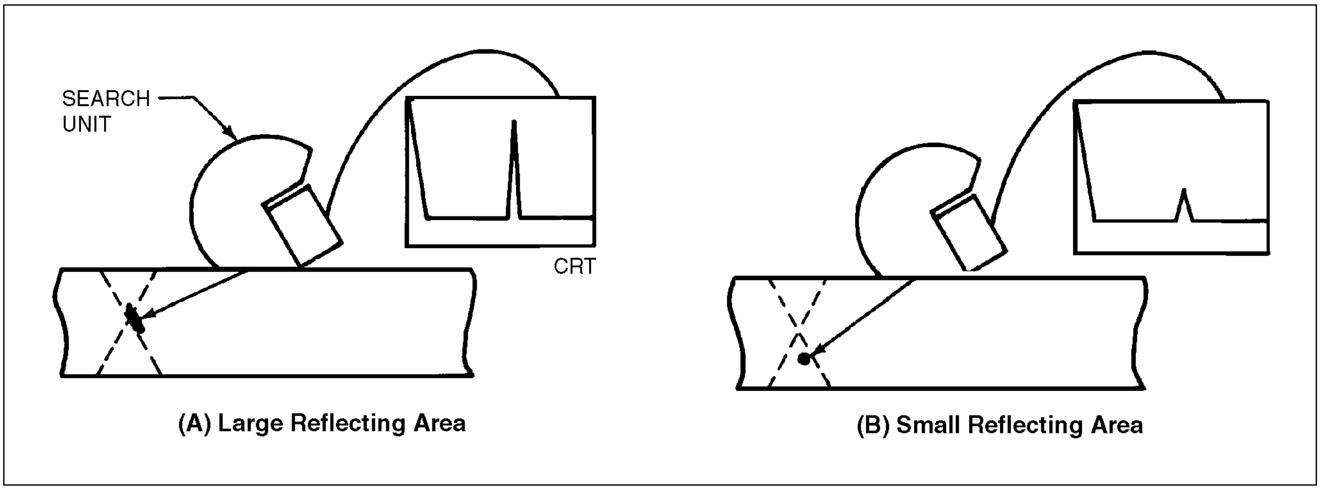


Figure 14.17—Size of the Reflecting Area Indicated by Echo Height

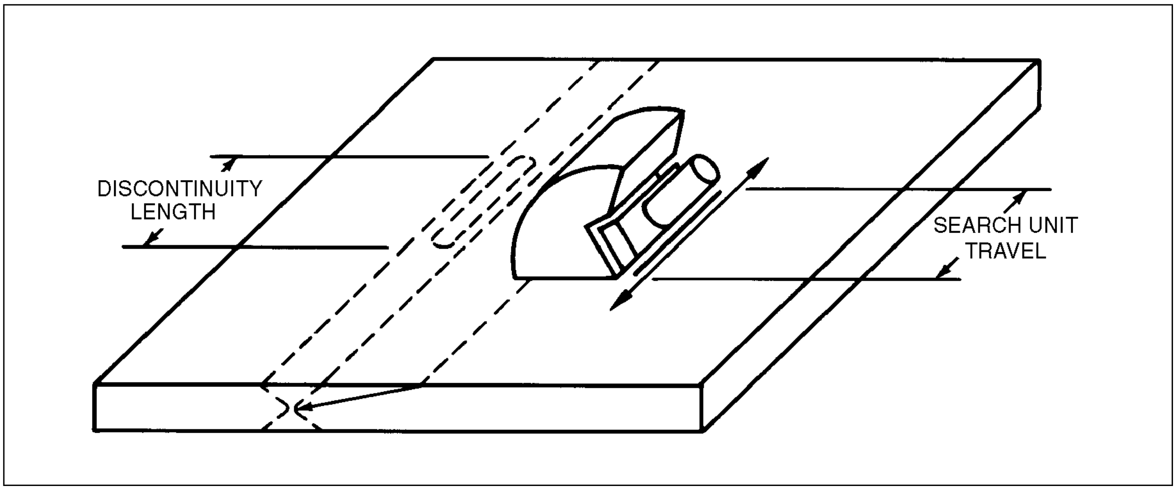


Figure 14.18—Discontinuity Length Determined from Search Unit Travel Distance

Advantages and Limitations

Ultrasonic examination offers a number of advantages when compared to other nondestructive examination methods for weldment inspection. Ultrasonic examination permits the detection of discontinuities in thick sections and has a relatively high sensitivity to small discontinuities. This method has the capacity to determine the depth of internal discontinuities and estimate their size and shape. It is also capable of performing adequate inspection from one surface. In addition, the equipment used in ultrasonic testing can be moved to the job site and is not hazardous to personnel or other equipment.

Although ultrasonic examination offers numerous advantages, this technique also possesses certain limitations. The principal limitations of ultrasonic testing are enumerated below:

1. The setup and operation of ultrasonic examination equipment require trained and experienced technicians, especially for manual examinations;
2. It is difficult or impossible to inspect weldments that are rough, irregular in shape, very small, or thin, including fillet welds;
3. Discontinuities at the surface are difficult to detect;

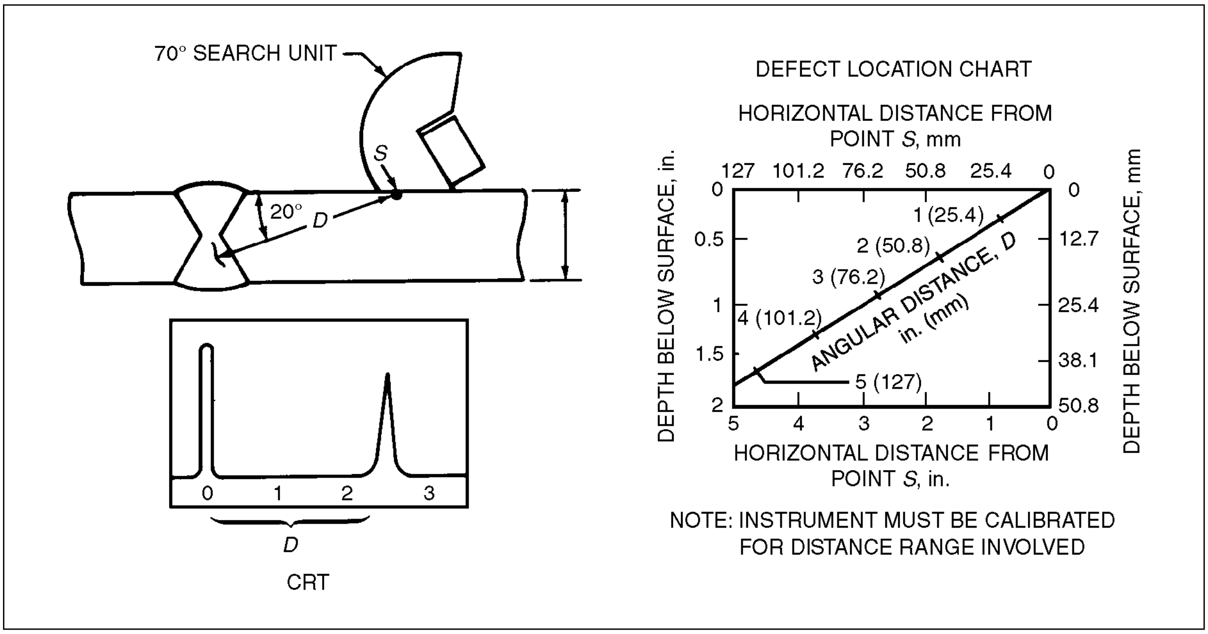


Figure 14.19—Estimating the Location of an Indication

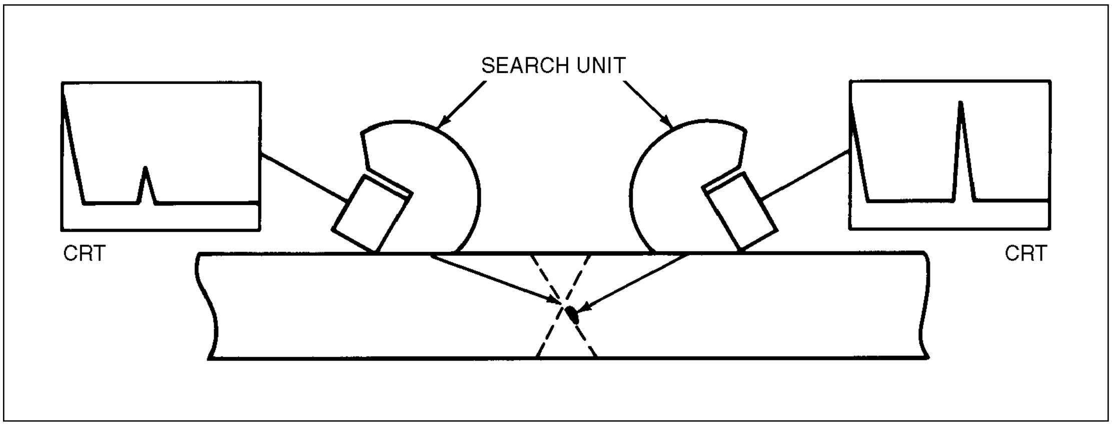


Figure 14.20—Discontinuity Orientation Indicated by Echo Height

4. A couplant is needed between the transducer and the weldment to transmit the ultrasonic wave energy;
5. Reference standards are required to calibrate the equipment and to evaluate the size of discontinuities; and
6. Reference standards must duplicate, to a reasonable degree, the item to be examined with respect to design, material specifications, and heat treatment condition.

MAGNETIC PARTICLE EXAMINATION

Magnetic particle examination (MT) is a nondestructive method used to detect surface or near-surface discontinuities in ferromagnetic materials.[26] This method is based on the principle that magnetic lines of force in

26. Additional information is provided in American Society for Testing and Materials (ASTM) Subcommittee E07.03, *Standard Guide for Magnetic Particle Examination*, ASTM E 709, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

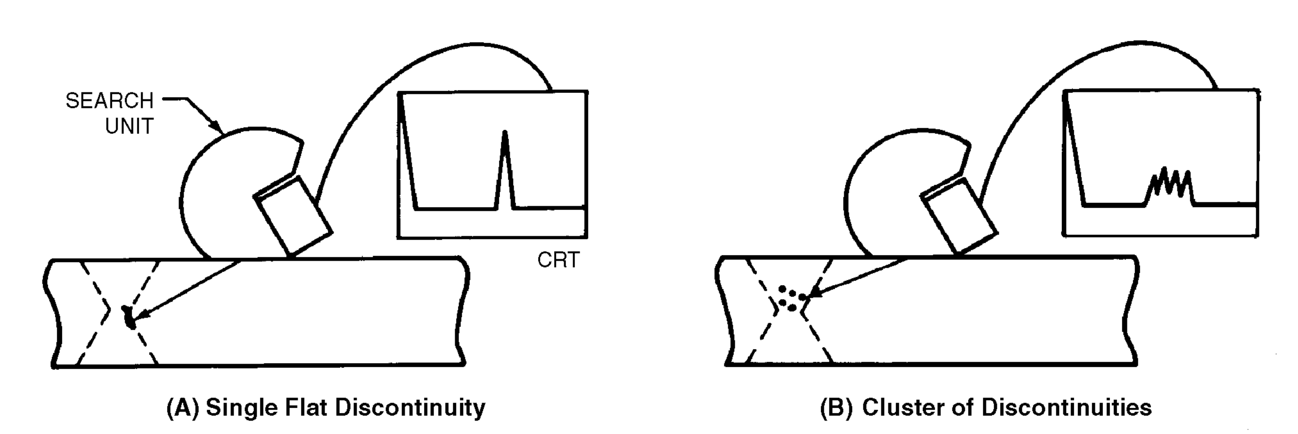


Figure 14.21—Discontinuity Type and Shape Indicated by Echo Shape

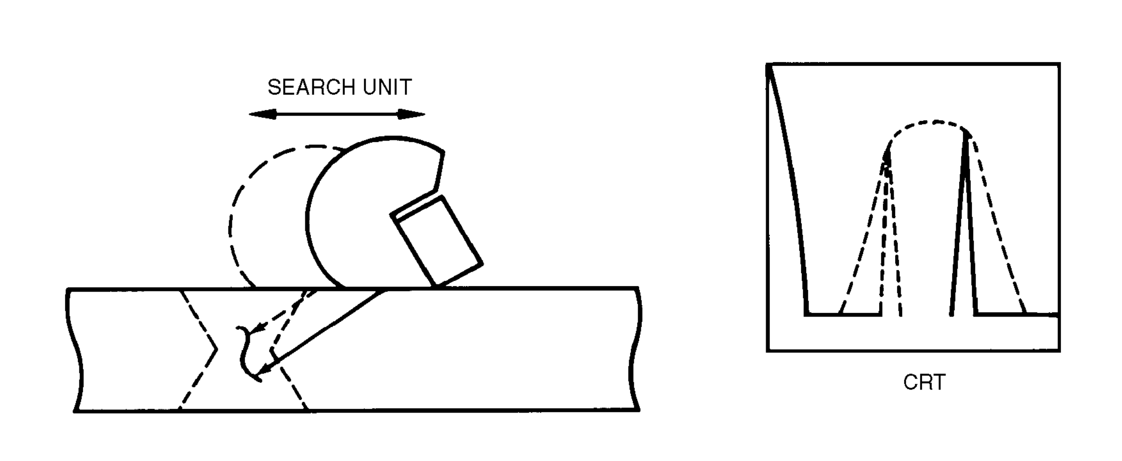


Figure 14.22—Estimating the Height of the Indication within the Weld

a ferromagnetic material are distorted by a distinct change in the continuity of the material. Examples of such a change are a discontinuity or a sharp dimensional change.

If a discontinuity in a magnetized material is open to or close to the surface, the magnetic flux lines are distorted at the surface. This condition is termed *flux leakage*. When fine iron oxide particles are distributed over the area of the discontinuity while the flux leakage exists, they accumulate at the site of the flux leakage and are held in place. This principle is illustrated in Figure 14.23. The accumulation of particles is visible under proper lighting conditions. While variations in the magnetic particle method exist, they are all dependent on the principle that magnetic particles are retained at the locations of magnetic flux leakage.

The essential requirements of magnetic particle examination are few. The test specimen must be magnetized. The magnetic particles must be applied while the specimen is magnetized, and any accumulation of magnetic particles must be observed and interpreted.

A ferromagnetic material can be magnetized by either passing an electric current through the material or by placing the material within a magnetic field originated by an external source. The entire component, or a portion of it, can be magnetized as dictated by size and equipment capacity or by need. As noted, the discontinuity must distort the normal path of the lines of mag-

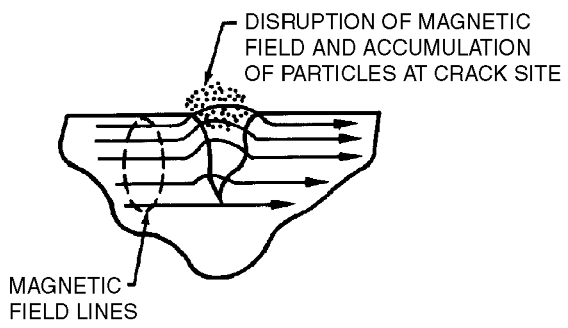


Figure 14.23—Magnetic Particles Attracted to Discontinuities by Flux Leakage

netic flux to the surface. When the discontinuity is open to the surface, the flux leakage is at a maximum for a given size and shape of discontinuity. When the discontinuity is below the surface, flux leakage is lower. Discontinuities must be open to the surface or must be in the near subsurface to create flux leakage of sufficient strength to accumulate magnetic particles.

When a discontinuity is oriented nearly parallel to the flux lines, it is essentially undetectable. Because discontinuities can occur in any orientation, it is usually necessary to magnetize the specimen at least twice so that induced magnetic lines of force are produced in different directions, preferably 90° from one another, to perform an adequate examination. Although the flux lines must be of sufficient density to indicate discontinuities that are unacceptable, they must not be so strong that an excess of particles accumulates locally, thereby masking relevant indications.

Applications

Magnetic particle examination is used extensively in the inspection of weldments. This process assists in the determination of the quality of welds in ferrous and other ferromagnetic materials. Considerable magnetic particle examination is performed on completed weldments. However, this inspection method can also be a valuable process feedback tool when used at prescribed intervals during the completion of a multiple pass weld. In this way, discontinuities are discovered when they can easily be corrected rather than later when the difficulty and cost of repair are greater.

Magnetic particle examination is used in the examination of the backgouged root of a groove weld or a repair excavation prior to subsequent welding. This ensures that all defects have been satisfactorily removed. This method is also applied to weldments following and sometimes prior to stress relief since most defects that occur during this treatment are surface related.

Magnetic particle examination is frequently applied to plate edges prior to welding for the detection of cracks, laminations, inclusions, and segregations. It reveals only those discontinuities that are near the edge or extend to the edge being examined. Although not all discontinuities found on plate edges are objectionable, it is necessary to remove those that would affect either the soundness of the welded joint or the ability of the base metal to meet the design requirements.

Magnetic particle examination can also be implemented in conjunction with repair work or rework procedures on new parts as well as on parts that may have developed cracks in service. This applies not only to the repair of weldments but also to rework done by welding in the repair or salvage of castings and forgings. The completed repair should be examined for cracks or other objectionable discontinuities in the weld or in the adjacent metal before the workpiece is placed in service. In general, the same examination procedures should be used in connection with repair or rework as would be used on the original parts.

Limitations

The magnetic particle examination method is most applicable for the examination of ferromagnetic metals in which the deposited weld metal is also ferromagnetic. It cannot be used to inspect nonferromagnetic metals such as austenitic stainless steels. Moreover, difficulties may arise in the application of this method when the magnetic characteristics of the weld metal are appreciably different from those of the base metal. Joints between metals with dissimilar magnetic characteristics create magnetic discontinuities that may produce indications in spite of the fact that the joints themselves are sound.

It has also been shown that subsurface porosity and slag inclusions produce powder patterns that are not clearly defined. The degree of sensitivity of this method depends upon certain factors. Sensitivity decreases with a decrease in size of the discontinuity and with an increase in depth below the surface. A decrease in sensitivity is also evident when discontinuities are rounded or spherical rather than linear or crack-like because these shapes produce less distinct indications than linear shapes.

To be detected, a discontinuity must be sufficiently large to distort the magnetic field and cause external leakage. Elongated discontinuities such as seams, inclusions, or fine cracks do not normally distort a magnetic field that is parallel to the direction of the discontinuity sufficiently to produce an indication.

Surface conditions also influence the sensitivity of magnetic particle examination. The surface of the weld and surrounding areas should be clean, dry, and free from oil, water, excessive slag, or other accumulations that interfere with magnetic particle movement. A rough surface decreases sensitivity by reducing particle mobility. Light grinding may be used to smooth rough weld beads. Care must be taken to avoid smearing the surface and leaving grinding marks on the surface.

Orientation of the Magnetic Field. The orientation of the magnetic field has a great influence on the validity and performance of magnetic particle examination. If testing is done on a weld using only a single orientation of the magnetic field, discontinuities that are aligned with the flux path may not be detected. Thus, the direction of the magnetic field must be known so that it can be shifted to provide the necessary coverage. The best results are obtained when the magnetic field is perpendicular to the length of the discontinuities.

Circular Magnetization. A magnetic field is produced by passing an electrical current through a conductor. This method is referred to as *circular magnetization*. Most magnetic particle examinations utilize this principle to produce a magnetic field within the workpiece. An electrically induced magnetic field is highly directional. The intensity of the field is proportional to the strength of the current. The direction of the magnetic lines of force in circular magnetism is shown in Figure 14.24.

When current is passed through a nonmagnetic conductor, a magnetic field is present on the surface of the conductor as well as around it. However, when current is passed through a ferromagnetic conductor such as carbon steel, most of the field is confined within the conductor itself. This behavior is illustrated in Figure 14.25.

When current is passed through a uniform section of steel, the resulting magnetic field is uniform as well. Upon applying the fine magnetic particles to the surface of the steel while the current is flowing, the particles become uniformly distributed over the surface. If a discontinuity is present on the surface, the particles tend to build up across the discontinuity because they are attracted by the magnetic flux leakage.

When the excess magnetic powder is removed, the outline of the discontinuity is well defined by the powder that remains, provided that the discontinuity is nearly perpendicular to the flux path. This phenomenon is illustrated in Figure 14.26. If the flux path is nearly parallel to the discontinuity, it is possible that no indication will appear. For a very large discontinuity parallel to the flux path, an indication might be visible, though it would probably be weak and indefinite.

When circular magnetization is utilized to detect longitudinal discontinuities positioned on the inner surface of a hollow workpiece, a slightly different technique is required because the inside surface is not magnetized when current passes directly through the part. This occurs because electric current tends to travel along the outside surface of a conductor. First, a conductor is placed through the opening or hole in the hollow workpiece. The current is then passed through the conductor, and circular magnetic fields are induced at the inner surface of the hollow workpiece and to a lesser degree at the outer surface, depending on the thickness of the workpiece.

Longitudinal Magnetization. Discontinuities are sometimes oriented parallel to the circular magnetic flux in a steel part. The detection of such discontinuities requires a different technique. A conductor is coiled, and the workpiece to be tested is placed within the coil such that it becomes the core of a solenoid. This produces a magnetic field in line with the axis of the coil. Two or more poles are produced, usually at the ends of the part. This technique is referred to as *longitudinal* or *bipolar magnetization*. As shown in Figure 14.27, longitudinal magnetization reveals discontinuities lying nearly transverse to the long axis of the part. Flaws oriented at 45° can be detected by circular or longitudinal magnetization.

When magnetic particle examination equipment is not available at the test site, longitudinal magnetization can be induced in parts such as shafts, pipes, and beams by coiling a length of welding cable around the area to be tested and then applying current. This technique is limited to small parts, however, because most welding power sources provide insufficient amperage for an effective magnetic particle examination.

Localized Magnetization. For large workpieces, two types of equipment can produce a magnetic field in a localized area. Both types can be utilized as portable methods for examination on location.

The first of these techniques is referred to as *prod magnetization*. With this method, a localized area can be magnetized by passing current through the workpiece by means of hand-held contacts or prods, as shown in Figure 14.28. Manual clamps or magnetic leeches can be used in place of prods.

The current creates local circular magnetic fields in the area around the contact points. This method is used extensively for the localized inspection of weldments in which the area of interest is confined to the weld zone. It is very important that the prods be held securely in contact with the workpiece to avoid arcing at the contact points and the creation of "prod marks" or arc strikes, which could produce an undesirable metallurgical condition. As this method provides a unidirectional magnetic field only, it is necessary to reorient the contacts at about 90° and remagnetize the workpiece for complete inspection of the area.

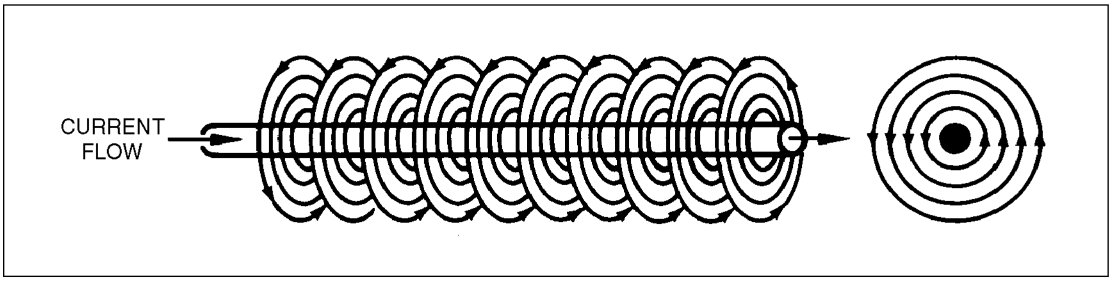


Figure 14.24—Magnetic Force Lines Around a Conductor

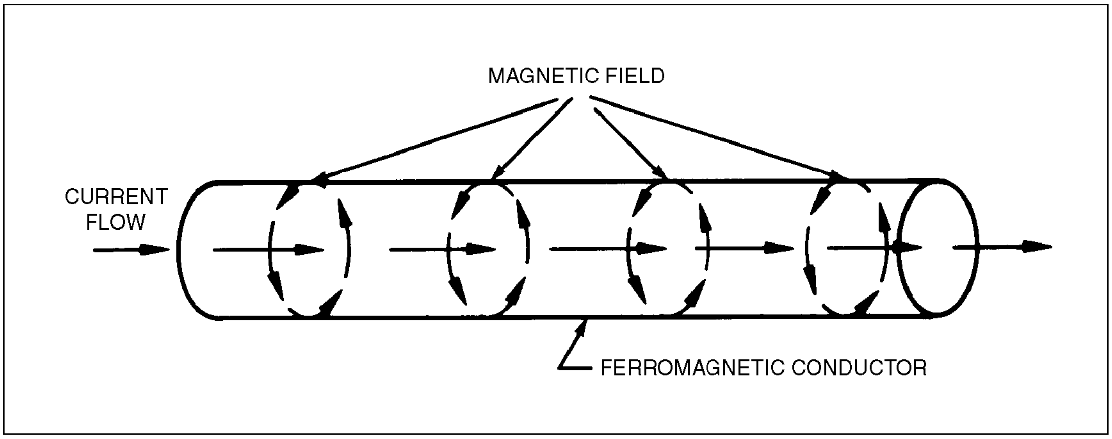


Figure 14.25—Magnetic Force Lines Within a Ferromagnetic Conductor

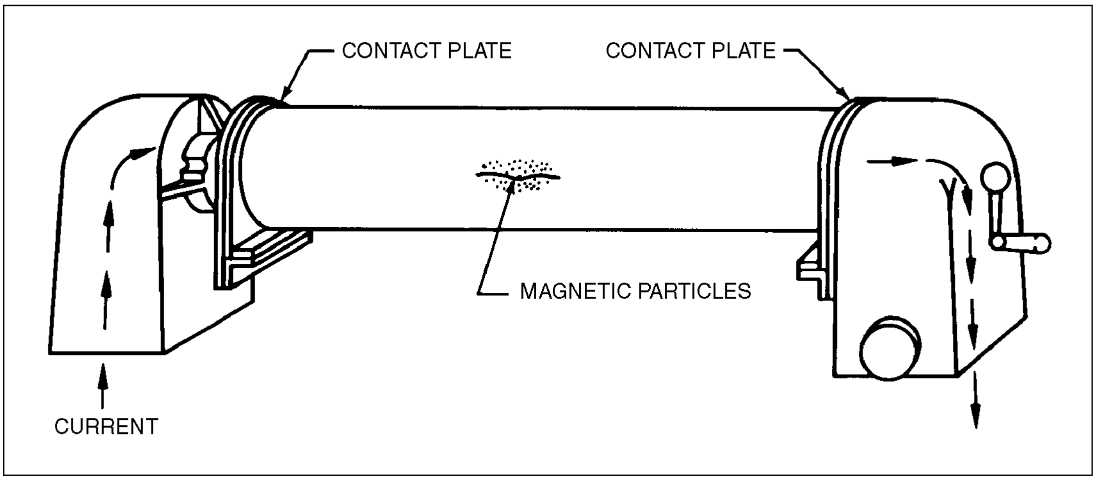


Figure 14.26—Accumulation of Magnetic Particles on a Discontinuity While Using Circular Magnetization

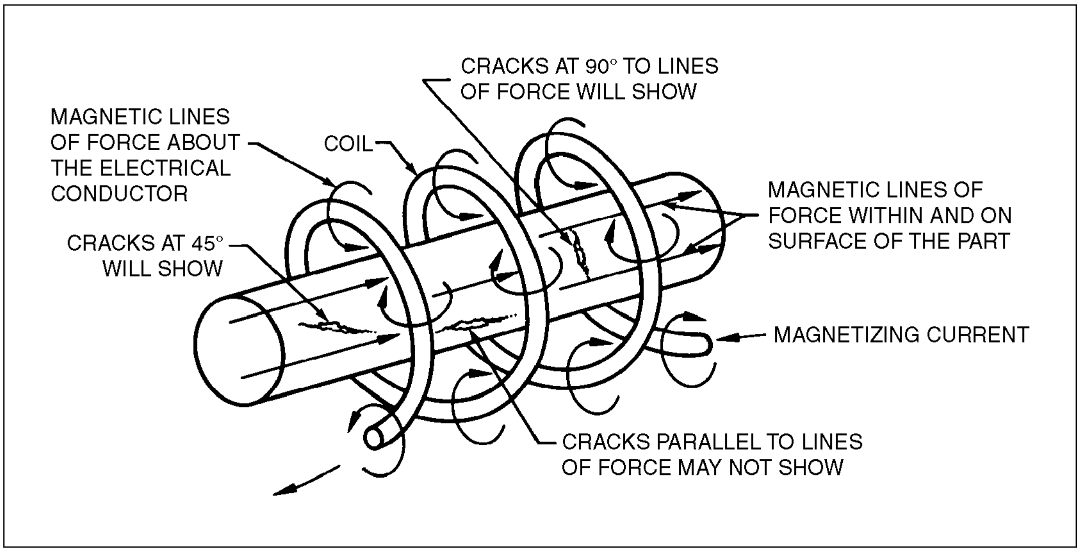


Figure 14.27—Accumulation of Magnetic Particles on Discontinuities Using Longitudinal Magnetization

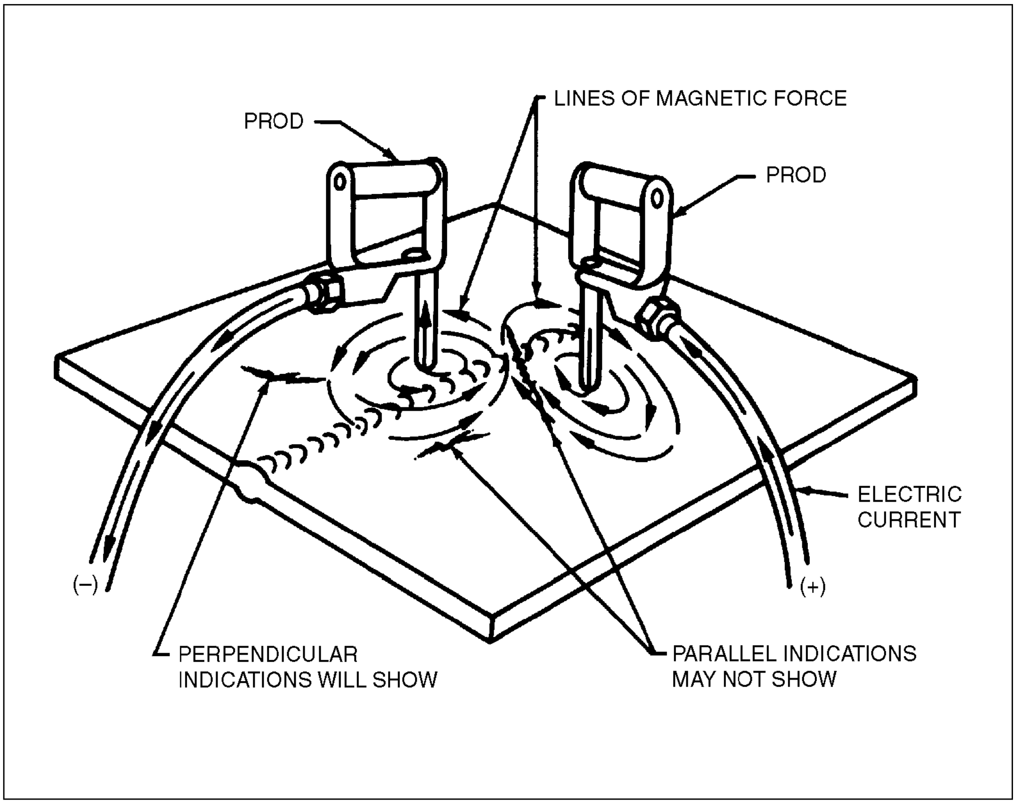
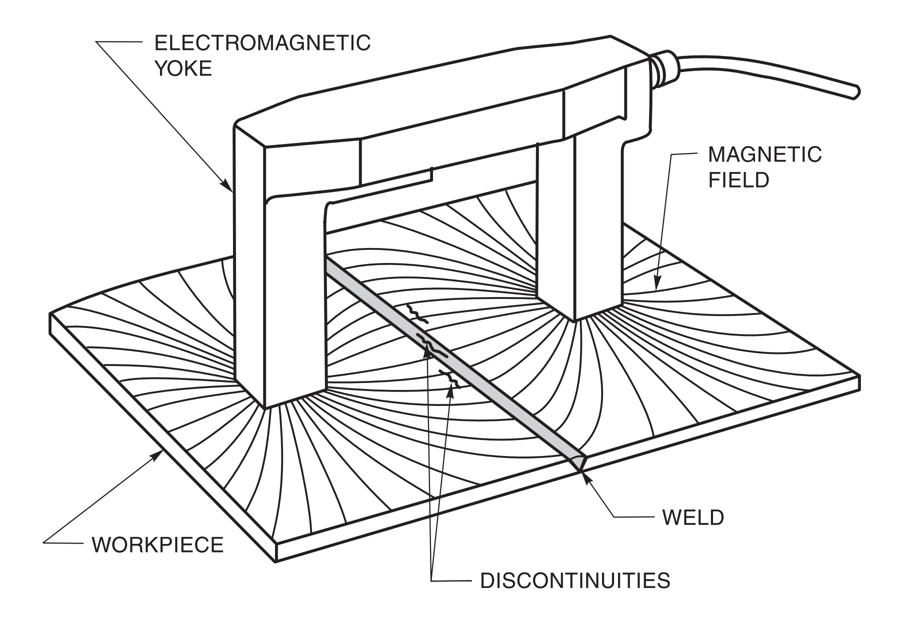


Figure 14.28—Local Magnetization of a Weld Using the Prod Technique



Source: Adapted from Lindgren, A., 1989, Magnetic Particle Inspection, in *Nondestructive Evaluation and Quality Control*, Vol. 17 of *ASM Handbook*, 9th ed., Metals Park, Ohio: ASM International, Figure 6.

Figure 14.29—Local Magnetization of a Weld Using the Yoke Method

A localized magnetic field can also be induced with an electromagnetic yoke having flexible low-carbon steel extensions of the core. When the two extensions make contact with the workpiece and the yoke is energized, the magnetic field of the yoke is concentrated in the part between the contact points. Referred to as the *yoke method*, this technique utilizes equipment that is relatively small and lightweight. Another desirable feature of this technique is that electric current is not transferred to the workpiece as with the prod method. Thus, arcing or burning of the workpiece does not occur. This technique is referred to as *indirect magnetization*. The application of the yoke method for the examination of a weld is shown in Figure 14.29.

Examination Procedures

When magnetic particle examination is used, a standard normally governs both the methodology and the criteria for acceptance and rejection. Most standards dictate the maximum permissible size of a discontinuity and the minimum distance between otherwise acceptable discontinuities. Some standards, including the set of AWS structural welding codes, also require that discontinuities be a minimum distance from the end of the weld. Like other nondestructive examination methods, magnetic particle examination should be performed according to a written procedure that specifies evaluation parameters. These are discussed below.

Magnetizing Current. Alternating current (ac) or direct current (dc) can be used to magnetize test specimens. High-amperage, low-voltage power is usually employed in magnetic particle examination. Portable equipment that makes use of electromagnets or permanent magnets is also occasionally used. These magnets are satisfactory for the detection of surface cracks only. The adequacy of the magnetic flux is usually verified by lifting specified weights with the magnets.

When alternating current is applied, the surface of the metal is magnetized. The method is effective for the location of discontinuities such as cracks that extend to the surface. However, deeper discontinuities and incomplete fusion are usually not detected. Alternating current may be used satisfactorily when subsurface evaluation is not required.

Direct current produces a magnetic field that penetrates deeper into the workpiece. It is therefore more effective than alternating current for the detection of subsurface discontinuities. Full-wave, rectified, three-phase current produces results that are essentially comparable to the uniform direct current obtained from a generator or batteries.

Half-wave, rectified, single-phase current provides maximum sensitivity. The pulsating field increases particle mobility and enables the particles to line up more readily in weak leakage fields. This technique also has the capability of detecting subsurface discontinuities.

With suitable equipment, two different types of current can be applied to a test specimen. The characteristics of the indications produced by the different currents provide useful information for a more accurate interpretation of a discontinuity. For example, by using both alternating- and direct-current magnetization, the relative amounts of particle buildup might help determine the depth of the discontinuity. If the particle buildup with the application of direct-current magnetization is considerably greater than that with alternating current, it is highly probable that the discontinuity has a significant depth and is not just a surface irregularity.

The magnetizing current should be of sufficient strength to indicate all detectable discontinuities that might affect the performance of the weldment in service. As excessive magnetizing currents produce irrelevant patterns, they should be avoided. The strength of the magnetizing currents should be specified in the test procedures or specifications; otherwise, current requirements may be determined by experience or experiment. The applied voltage, which has no effect on the magnetic field strength, should be kept low to prevent arcing and overheating.

The approximate amperage ranges for the various magnetizing methods are as follows:

1. For longitudinal magnetization, a range of 3000 to 10,000 ampere-turns should be used, depending on the ratio of the coil and workpiece diameters;
2. For overall circular magnetization, a range of 100 amperes (A) to 1000 A per 1 in. (25.4 mm) of workpiece diameter should be used;
3. For prod magnetization, 90 A to 125 A per 1 in. (25.4 mm) of prod spacing, depending on metal thickness is recommended; and
4. For yoke magnetization, the magnetizing current must be sufficient to lift 40 lb (18 kg) with direct-current magnetization and 10 lb (5 kg) with alternating-current magnetization.

Selection of Inspection Media and Method. Magnetic particles of various colors, mobility, and luminescence are available. Colors include red and black. The red particles are better for dark surfaces. A suitable particle type can be selected to provide the greatest visual sensitivity for each specific test situation. The use of particles coated with a dye that fluoresces brilliantly under ultraviolet (black) light increases the sensitivity of the test. Fluorescent particles can indicate very small or fine discontinuities and permit the rapid inspection of irregular or dark surfaces. The condition of the test surface and the types of discontinuities suspected are additional criteria to be considered in the selection of magnetic particles. Dry and wet examination methods are commonly used.

In the dry method, finely divided ferromagnetic particles in dry powder form are coated to provide for enhanced mobility. They are then dyed various colors to create a distinct contrast with the background. The dyed particles are applied uniformly to the workpiece by means of a particle dispenser, an atomizer, or a spray gun. Dry powder is most satisfactory on rough surfaces. The powder should be applied in the form of a low-velocity cloud with just enough motive force to direct the particles to the area of interest. This permits the particles to line up in indicating patterns as they are drawn to locations of flux leakage. The excess powder should be removed using a stream of air that is low in velocity but sufficient to carry the excess powder away without disturbing the lightly held powder patterns.

Wet magnetic particle examination is better suited for the detection of fine surface discontinuities on smooth surfaces. Conversely, it is less likely to reveal a subsurface discontinuity than the dry method. The magnetic particles used for wet magnetic particle examination, which are smaller than those used in the dry method, are suspended in a liquid bath. The magnetic particles for liquid suspension are available in either paste or concentrate form for use with either an oil or a water bath. For proper testing sensitivity, the manufacturer's recommendations should be observed when preparing the bath. Aerosol cans containing premixed particle-bearing suspensions are also commercially available. Continuous agitation of the solution is necessary to prevent the suspended particles from settling and reducing the sensitivity.

Both oil-based and water suspensions provide nearly equal sensitivity. The use of the water suspension prevents a fire hazard due to arcing, but the presence of water near electrical apparatus creates a shock hazard that must be guarded against. Operators must be cognizant of potential hazards and informed regarding their prevention.

During examination with the wet technique, the magnetic particle solution is either flowed over or sprayed on the area of interest. The workpiece can also be immersed in a tank containing the liquid bath. The smaller the size of the particles, the greater the test sensitivity. Very fine discontinuities can be revealed consistently with this method.

Sequence of Operation. In magnetic particle examination, the sequence of operation involves both the timing and the application of the particles and the magnetizing current. Two basic sequences, continuous and residual, are typically employed. Continuous magnetization using either wet or dry particles is employed for most applications. The sequence of operation differs for the wet and dry techniques.

The wet technique is generally used for those parts processed on a horizontal, wet-type testing unit. In practice, it first involves bathing the workpiece with the inspection medium to provide an abundant source of suspended particles on the surface. The bath is then terminated, and at the same time, the magnetizing current is initiated. The duration of the magnetizing current is typically one-half a second. With the dry technique, the particles lose mobility when they contact the surface of a part. Therefore, it is imperative that the workpiece be under the influence of the applied magnetic field while the particles are still airborne and free to migrate to leakage fields. The flow of the magnetizing current must be initiated prior to the application of dry magnetic particles, and it must be continued until the application of powder has been completed and any excess has been blown off. Half-wave rectified or alternating current provides additional particle mobility on the surface of the part, which can be an asset. Examination with dry particles is usually performed with prod or yoke localized magnetization.

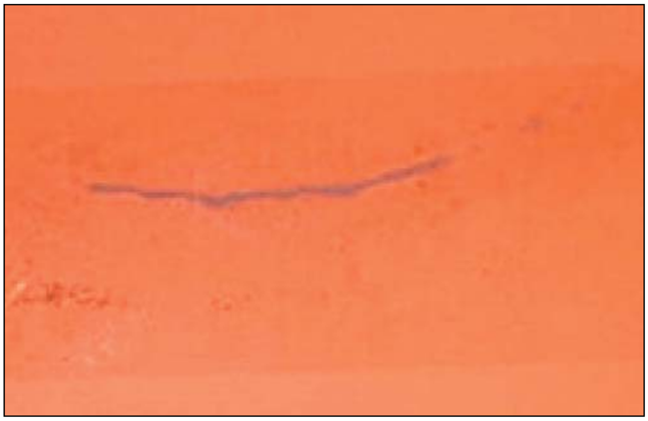
In residual magnetization, the particles are applied after the magnetizing current has been discontinued. This method can be used only if the weldment being examined has relatively high retentivity so that the residual magnetic field is of sufficient strength to attract and hold the particles at discontinuities. This technique should not be used unless experiments with typical parts indicate that the residual magnetic field has sufficient strength to produce satisfactory indications. The equipment used in residual magnetization testing must be designed to provide a consistent, quick interruption of the magnetizing current.

Recording Results. Examination equipment is enhanced when combined with a system that consistently and accurately records test results. If repair is to take place immediately following the examination, the powder buildup that remains is used to identify the affected area. However, a permanent test record is required in many cases. In these cases, the actual powder buildup can be preserved using the following technique.

After the discovery of a magnetic particle indication like that shown in Figure 14.30, a piece of transparent pressure-sensitive tape sufficiently large to cover the entire area of interest can be carefully applied to the surface over the indication. For location determination, it may be helpful to extend the tape to include other nearby reference locators such as holes and key ways. Upon removal of the tape from the surface of the part, the magnetic particles remain on the tape to provide an accurate record of the shape, extent, and location of the indication. This tape is then applied to a piece of paper with a color contrasting that of the magnetic particles being used, as shown in Figure 14.31. Sketches may be necessary to clarify the exact location of the indication.

Photograph courtesy of the Edison Welding Institute

Figure 14.30—MT Indication of a Toe Crack in a Pipe Weld



Photograph courtesy of the Edison Welding Institute

Figure 14.31—MT Indication Transferred via the Transparent Tape Lift-Off Technique

On occasion, it may be helpful to provide better contrast of the indications on the part. Better contrast can be obtained by spraying the workpiece with white paint prior to examination to provide a white background for a dark magnetic particle indication.

The use of photographs aided by the inclusion of location markers and a measuring device provides a method of capturing inspection results. These lasting visual records of an inspection are especially useful for recording the successful removal of weld or base metal defects, as-found cracks, and other defects in completed welds. These records can also be used in future failure analysis, particularly if the weldment has been in service, as the photographs indicate the condition of the surrounding area as well.

Demagnetization. Ferromagnetic steels exhibit varying amounts of residual magnetism after being magnetized. In some service situations, a residual magnetic field remaining in a component would be detrimental, making demagnetization necessary. An example is a component that is to be located close to a device that is affected by magnetic fields, such as a compass, an instrument, computers, or electrical equipment.

The demagnetization of small parts can be accomplished by inserting each one into the magnetic field of a strong alternating-current coil and then gradually withdrawing it from the field. Alternatively, each workpiece is subjected to an alternating magnetic field that is gradually reduced in intensity.

With massive structures, alternating current does not work because the magnetic field cannot penetrate sufficiently to accomplish complete demagnetization. In such cases, direct-current magnetization should be used. The current should be gradually reduced to zero while undergoing cyclic reversals. Hammering on the component or rotating it in the magnetic field sometimes assists demagnetization.

Annealing, or stress-relief heat treatment, partially demagnetizes steel weldments. Total demagnetization is always accomplished when the weldment is heated above the Curie temperature, which is 1414°F (768°C) for carbon steel.

Relevant Discontinuity Indications

Magnetic particle powder indications of discontinuities must be evaluated to determine compliance with the governing standard. Indications have a variety of configurations based on the flux leakage field caused by the discontinuity. Indication characteristics such as height, width, shape, and sharpness of detail provide information as to the type and extent of the discontinuity. Certain discontinuities exhibit characteristic powder patterns that can be identified by a skilled operator. Some of the typical discontinuity indications are discussed below.

Surface Cracks. The indication exhibited by a surface crack is well defined and tightly held with heavy powder buildup.

Subsurface Cracks. Cracks that have not broken to the surface exhibit indications that are different from those manifested by surface cracks. The powder buildup is slightly wider and not well defined.

Incomplete Fusion. For incomplete fusion, the magnetic particle indication is fairly well defined, but this discontinuity may only occur at the edge of a weld pass. The indication is not sharp because incomplete fusion is rarely visible on the surface.

Slag Inclusions and Porosity. Subsurface slag inclusions and porosity can be found, but the magnetic particle indications are very vague unless the extent of the slag inclusions and porosity is severe. Powder buildup is not clearly defined but can be distinguished from surface indications.

Incomplete Joint Penetration. Under certain conditions, incomplete joint penetration can be located with magnetic particle examination. The powder indication is wide and fuzzy, like that for a subsurface crack, but the pattern is linear along the centerline of the weld.

Laminations. When plate edges or weld preparations are examined prior to welding, plate-rolling laminations may be detected. The magnetic particle indications are significant and very distinct. They may be continuous or intermittent.

Seams. Indications of seams in plate are straight, sharp, fine, and often intermittent. Powder buildup is less significant. The use of a magnetizing current greater than that required for the detection of cracks may be necessary.

Undercut. Surface indications for undercut are located at the toe of groove or fillet welds. They are slightly less well defined than the indications of inadequate joint penetration. Visual inspection is probably a better method to evaluate this discontinuity.

Nonrelevant Indications

Magnetic powder can collect at any location where a disturbance in the magnetic field exists. When these indications do not result from a mechanical discontinuity, they are not related to the soundness of the weld nor do they affect the service performance of the weld. Most nonrelevant indications can be properly identified with experience, but some codes require that all nonrelevant indications be regarded as relevant until their nonrelevance can be verified by re-examination with the same or other nondestructive examination methods. Once these indications are verified as nonrelevant, the standards allow repetitive nonrelevant indications of the same type to be ignored unless they mask the detection of valid indications. Some of the more commonly encountered nonrelevant indications are discussed below.

Surface Finish. When a weld has a rough or irregular surface, the powder often builds up and renders false indications. Grinding the weld face smooth followed by examination should determine the relevancy of any indications.

Magnetic Characteristics. Differences in magnetic characteristics in a welded joint can occur by means of several mechanisms, but all result in nonrelevant indications. Consequently, some cases may warrant the use of a different nondestructive examination to check the weld quality. A change in magnetic characteristics can take place in the heat-affected zone. The resulting indications run along the edge of the weld and are fuzzy. The pattern is often mistaken for that produced by undercut, but it is less tightly held. Postweld thermal stress relief can sometimes eliminate this phenomenon.

Another change in magnetic characteristics is noted when two metals of differing magnetic properties are joined or when the filler metal and the base metal have different magnetic properties. This commonly occurs in the joining of carbon steel (ferromagnetic) and austenitic stainless steel (nonferromagnetic). Another common occurrence arises when austenitic stainless steel filler metal is used to make a repair in carbon steel. In this case, a nonrelevant indication forms at the junction of the two. It appears sharp and well defined, much like a crack.

Banding. Banding occurs when the magnetizing current is too high for the volume of metal subjected to the magnetic field. When banding is encountered, the current should be reduced or the prod spacing increased to prevent the possible masking of real flaws.

Residual Magnetism. The lifting of steel with electromagnets or contact with permanent magnets may result in false indications from the residual magnetism in the steel.

Cold Working. The cold working of magnetic steel sometimes changes the local magnetic characteristics so that the zone will hold powder. This can occur when the surface of a steel weld is marred by a blunt object. In this case, the track appears as a fuzzy, lightly held powder buildup.

LIQUID PENETRANT EXAMINATION

Liquid penetrant examination (PT) is a method that reveals surface-breaking discontinuities by the bleedout of a liquid penetrant medium against a contrasting background developer. The technique is based on the ability of a penetrating liquid to wet the surface opening of a discontinuity and then be drawn into it. If the discontinuity is significant, penetrant will remain in the cavity when the excess is removed from the surface. Upon the application of a liquid-suspended or dry powder developer, blotter action draws the penetrant from the discontinuity to provide a contrasting indication on the surface.

Applications

Penetrant examination, when properly performed, is reliable for the inspection of welds. Following visual examination, it is perhaps the most commonly used nondestructive examination method for the surface examination of nonmagnetic parts. While the method can be performed on as-welded surfaces, the presence of weld bead ripples and other irregularities may hinder the interpretation of indications. If a surface condition causes an excessive amount of nonrelevant indications, it may be necessary to remove troublesome imperfections by light grinding prior to inspection.

The visible penetrant method is commonly used for field testing applications because of its portability. Liquid penetrant examination can also be used to check the accuracy of results obtained in the magnetic particle examination of ferromagnetic weldments.

Liquid penetrant examination is a relatively inexpensive and reliable method for obtaining information on questionable welds. The following simple steps are normally followed in the application of a typical penetrant examination:

1. Clean the test surface,
2. Apply the penetrant,
3. Wait for the prescribed dwell time to expire,
4. Remove the excess penetrant,
5. Apply the developer,
6. Wait the prescribed time,
7. Examine the surface for indications and record the results, and
8. Remove the residue.

It is important to note that when the order of these steps is changed or short cuts are taken, the validity of the examination is considered suspect.

Liquid penetrant methods can be divided into two major groups, depending on the type of penetrant used. For Type A, the penetrating medium is fluorescent, meaning that it glows when illuminated by ultraviolet or black light. Type A testing is shown in Figure 14.32. Type B employs a visible penetrant, usually red in color, which produces a contrasting indication against the

Figure 14.32—Florescent Penetrant Illuminated by Ultraviolet Light

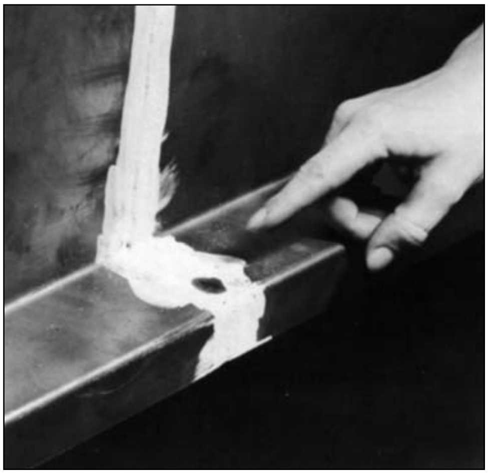


Figure 14.33—Red Penetrant Contrasted Against White Developer

white background created by the developer. The application of Type B is shown in Figure 14.33.

Although sensitivity is greater using the fluorescent method, both methods provide extremely good sensitivity when properly applied. The difference in sensitivity is due to the fact that the eye can discern the contrast of a fluorescent indication under black light more readily than a color contrast under white light. In the latter case, the area must be viewed with adequate white light.

Required Equipment and Materials

Unlike many of the other types of nondestructive examination, liquid penetrant examination requires little equipment. The equipment consists of containers and applicators for the various liquids and solutions that are used. The examination materials are available in convenient aerosol spray cans that can be purchased separately or in kits. Fluorescent penetrant examination requires a high-intensity ultraviolet light source and facilities for the reduction or elimination of outside lighting. Other related equipment—additional lighting, magnifiers, drying apparatus, rags, paper towels, and so forth—might be needed depending on the specific application.

Liquid penetrant examination materials consist of fluorescent and visible penetrants, emulsifiers, solvent base removers, and developers. As these materials can be flammable or emit hazardous and toxic vapors, it is imperative to observe all the manufacturer's instructions and precautionary statements. The intermixing of materials of different types and produced by different manufacturers is not recommended; in fact, this practice is prohibited by most codes. The examination materials used should not adversely affect the serviceability of the parts examined. Care must be taken to ensure the compatibility between the penetrant materials and the parts being inspected.

Penetrants. Water-washable penetrants are designed to wash directly off the surface of the test specimen after a suitable penetrating (dwell) time. It is important to avoid overwashing because the penetrants can be washed out of discontinuities if the rinsing lasts too long or is too vigorous.

Postemulsifiable penetrants are insoluble in water and cannot be removed by rinsing with water alone. They must first be treated with an emulsifier. The emulsifier combines with the penetrant to form a water-washable mixture, which can be rinsed from the surface of the part.

Solvent-removable penetrants are removed by wiping the surface with a clean, lint-free material and repeating the operation until most traces of penetrant have been removed. The remaining traces are removed by wiping the surface with a clean, lint-free material that has been lightly moistened with a solvent remover. Solvent-removable penetrants are designed primarily for portability and the inspection of small areas. The use of excess solvent must be avoided to minimize the removal of penetrant from discontinuities.

Emulsifiers. Emulsifiers are liquids used to make the penetrant water-soluble so that excess penetrant can be washed from the surface. The postemulsified penetrant method is the most sensitive. Because the amount of excess penetrant that is removed can be controlled, this method can be used on rough surfaces with better results than those provided by other techniques.

Developers. Dry powder developers are free-flowing and noncaking. Care should be taken not to contaminate the developer with penetrant. Aqueous wet developers are normally supplied as dry powders to be suspended or dissolved in water, depending on the type of developer.

Nonaqueous suspendible developers are supplied as suspensions of developer particles in nonaqueous solvent carriers ready for use as supplied. They are applied to the area by conventional or electrostatic spray guns or by aerosol spray cans after the excess penetrant has been removed and the workpiece has dried. When dried, nonaqueous wet developers form a white coating on the surface of the part, which serves as a contrasting background for visible penetrants and as developing media for fluorescent penetrants.

Procedures

Two commonly applied liquid penetrant examination specifications are *Standard Test Method for Liquid Penetrant Inspection,* ASTM E 165[27] and *Standard Reference Photographs for Liquid Penetrant Inspection,* ASTM E433.[28]

The following general processing procedures, outlined in Figure 14.34, apply to both the fluorescent and visible penetrant testing methods. The temperature of the penetrant materials and the surface of the weldment should normally range between 60°F and 125°F (16°C and 52°C). However, special penetrant materials are available for applications up to temperatures of 600°F (316°C). To ensure accurate results, procedures should be qualified when examination is to occur outside these normal temperature ranges.

Satisfactory results can usually be obtained on surfaces in the as-welded condition. However, surface preparation by grinding or machining may be necessary when surface irregularities might mask the indications of unacceptable discontinuities or otherwise interfere with the effectiveness of the examination.

Precleaning. The success of any liquid penetrant examination procedure is greatly dependent upon the freedom of both the weld area and any discontinuities from contaminants (soils) that might interfere with the penetrant. All parts or areas of the parts to be examined must be clean and dry before the penetrant is applied. For these purposes, "clean" is intended to mean that the surface must be free of any rust, scale, welding flux, spatter, grease, paint, oily films, dirt, or other material that might interfere with penetration. If only a section containing a weld is to be inspected, the weld and adjacent base metal must be cleaned thoroughly.

Drying After Cleaning. It is essential that the parts be thoroughly dry after cleaning because liquid residue hinders the entrance of the penetrant into the discontinuity. Drying may be accomplished quickly by warming the parts in drying ovens, with infrared lamps, or with forced hot air. However, workpiece temperatures must not exceed 125°F (52°C) prior to the application of the penetrant unless special qualification testing has been completed.

Penetrant Application. After the workpiece has been cleaned, dried, and cooled to approximate ambient temperature (125°F [52°C] maximum), the penetrant is applied to the surface to be inspected in such a manner so as to cover the entire workpiece or weld area. Various methods are used for the effective application of penetrant. These include dipping, brushing, flooding, or spraying. Small parts are often placed in suitable baskets and dipped into a tank of penetrant.

When working with larger workpieces and workpieces with complex geometry, the penetrant can be applied effectively by brushing or spraying. Aerosol sprays are also a very effective and convenient means of application. With spray applications, it is important to ensure adequate ventilation. This is generally accomplished with a properly designed spray booth and exhaust system. After application, excess penetrant is drained from the part.

The length of time the penetrant is allowed to remain on the workpiece to ensure proper penetration should be that recommended by the manufacturer or as required by the applicable code or procedure. Should the characteristics of the penetrant be materially affected by a prolonged dwell time, as evidenced by difficulty in removing the excess, the penetrant should be reapplied for the prescribed dwell time. The penetrant must remain wet throughout the entire dwell time to be effective. If the penetrant dries or is difficult to remove, it must be removed, and the entire examination process must be repeated.

Removal of Excess Penetrant. After the required dwell time, the excess penetrant is removed. The removal procedure depends on the type of penetrant used in the test. Water-washable penetrants can be removed directly from the surface of the workpiece using water spray or immersion equipment. Most

27. American Society for Testing and Materials (ASTM) Subcommittee E07.03, *Standard Test Method for Liquid Penetrant Examination,* ASTM E 165, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
28. American Society for Testing and Materials (ASTM) Subcommittee E07.03, *Standard Reference Photographs for Liquid Penetrant Inspection,* ASTM E 433, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

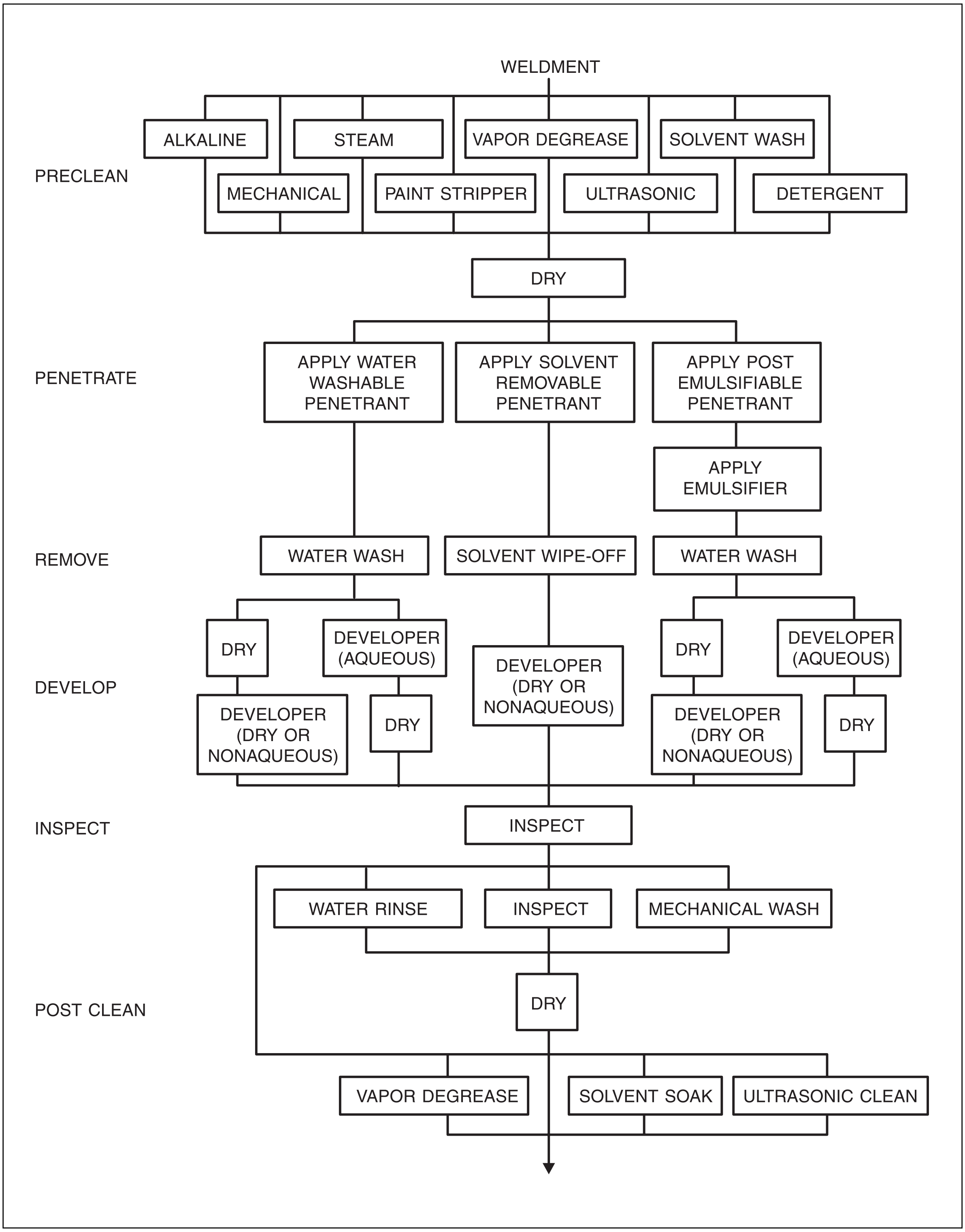


Figure 14.34—Flow Chart for Fluorescent and Visible Liquid Penetrant Examinations

water-washable penetrants can be removed effectively within a temperature range of 60°F to 110°F (16°C to 45°C), but for consistent results, the temperature recommended by the manufacturer should be observed.

Excessive washing may cause the penetrant to be washed out of existing discontinuities. Thus, the rinsing operation for fluorescent penetrants should be conducted under black light to indicate when the surface penetrant has been adequately removed. In special applications, when water rinse facilities are not available, the penetrant may be removed by wiping the surface with a clean, absorbent material dampened with water until the excess penetrant on the surface has been removed. Care must be taken not to remove too much penetrant.

As postemulsifiable penetrants are not directly water-washable, they require the use of an emulsifier (oil or water based). After the required dwell time, the excess penetrant on the workpiece is emulsified by dipping, flooding, or spraying the target area with the required emulsifier. After the application of the emulsifier, the workpiece should be drained to avoid the pooling of the emulsifier. Emulsification dwell time begins as soon as the emulsifier has been applied. Nominal emulsification time should be as recommended by the manufacturer. The effective rinsing of the emulsified penetrant from the surface of the workpiece can be accomplished in the same manner as that used for water-washable penetrants. Excessive emulsification dwell time causes the removal of penetrant from discontinuities.

With solvent-removable penetrants, excess penetrant is removed by wiping with a clean, lint-free material. This operation is repeated until most traces of penetrant have been removed. Then, a lint-free material is lightly moistened with solvent and wiped over the surface until all remaining traces of excess penetrant have been removed. The use of excessive solvent must be avoided to minimize the removal of penetrant from discontinuities.

When effective penetrant removal cannot be achieved using the procedure described above, it may be necessary to flush the surface with solvent. This operation might jeopardize the accuracy of the test. Therefore, for most applications, flushing the surface with solvent is prohibited. If this option is necessary, the solvent used may be one of several types, some of which are toxic, flammable, or both. Consequently, proper safety precautions must be observed. The producers of these materials also market compatible precleaners for their penetrant products, and their use is recommended.

Drying of Workpieces. During the preparation of workpieces for examination, drying is necessary following the removal of excess penetrant and prior to the application of developers. Workpieces can be dried using the procedures described above for drying after the initial cleaning operation.

The temperature of the workpiece should never exceed 125°F (52°C) unless high-temperature materials are being employed. Excessive drying temperature or time can cause the penetrant to evaporate, which may impair the sensitivity of the inspection. Drying time varies with the size, nature, and number of workpieces under inspection. When the excess penetrant is removed with the solvent wipe-off technique, drying occurs by means of evaporation.

Developing Indications. Indications are developed by drawing the penetrant back out of any discontinuities by means of blotting, which spreads the penetrant on the surface. Developing increases the visibility of the penetrant. Developers are used in dry form or suspended in an aqueous or nonaqueous solvent. They should be applied immediately after the excess penetrant has been removed from the surface of the workpiece, prior to drying in the case of aqueous developers and immediately after the workpiece has been dried for all other types of developer.

Several methods can be employed for the effective application of various types of developers. These techniques include dipping, immersing, flooding, spraying, and dusting. The size, configuration, surface condition, and number of parts to be processed determine the choice of developer.

Dry powder developers should be applied in a manner that assures complete coverage of the area to be inspected. Excess powder may be removed by shaking the part, tapping it gently, or by blowing with low-pressure (5 pounds per square inch gauge [psig] to 10 psig [34 kilopascal (kPa) to 69 kPa]) dry, clean compressed air.

Aqueous developers should be prepared and maintained in accordance with the manufacturer's instructions and applied in a manner to assure complete and even coverage. They should be applied immediately after the excess penetrant has been removed from the workpiece and prior to drying. The parts are then dried as described above. After drying, the developer appears as a white coating on the workpiece.

Nonaqueous wet developers are applied to the workpiece by spraying, as recommended by the manufacturer, after the excess penetrant has been removed and the workpiece has been dried. This type of developer includes a carrier that evaporates very rapidly at normal temperatures, leaving a white powder. It therefore does not require the use of a dryer. The developer must be sprayed in a manner that assures complete coverage with a thin, even film. It must be used with proper ventilation.

Developing begins immediately after the application of dry powder developer or as soon as a wet (aqueous or nonaqueous) developer coating is dry. At least seven minutes, or as recommended by the manufacturer, should be allowed to pass before the coated area is examined visually for indications. If bleedout does not alter the test results, development periods of over 30 minutes are permitted.

Examination. Although the evaluation of test specimens is performed after the appropriate development time, it is a good practice to observe the surface while applying the developer to aid in evaluating indications. The evaluation of fluorescent penetrant indications is carried out in a dark area. Maximum ambient light of about 3 footcandles (32 lux) is allowed for critical examination. Higher levels may be used for noncritical work. The intensity of the black light should be a minimum of 6250 microwatts per square inch ($\mu W/in.^2$) (1000 microwatts per square centimeter [$\mu W/cm^2$]) on the surface of the workpiece being examined.

Visible penetrant indications can be observed under natural or artificial white light. A minimum light intensity of 32.5 footcandles (350 lux) is recommended.

Postcleaning. Postcleaning is necessary in those cases in which residual penetrant or developer could interfere with subsequent processing or service requirements. This is particularly important in areas where residual examination materials might combine with other materials in service to produce corrosion products. A suitable technique such as simple water rinsing, machine washing, vapor degreasing, solvent soaking, or ultrasonic cleaning may be employed. In the case of developers, it is recommended that cleaning be carried out within a short time after evaluation to prevent the developer from adhering to the part. Developers should be removed prior to vapor degreasing as the heat can bake the developer onto the parts.

Interpretation of Indications. Surface cracks are probably the most common defects revealed by penetrant examination. Because surface cracks are critical for most applications, this test capability is a valuable one. An indication of a crack is very sharp and well defined. Most cracks exhibit an irregular shape, and the indication produced by the penetrant takes the same shape but is larger. The width and length of the bleedout is a relative measure of crack volume. Deep or wide cracks continue to produce an indication even after recleaning and redeveloping several times.

Surface porosity, metallic oxides, and slag also hold penetrant and cause an indication. Depending on the exact shape of the pore, oxide, or slag pocket, the indication takes a form that is relatively circular. In any case, the length-to-width ratio of the indication is usually far less than that of a crack.

Other discontinuities such as incomplete joint penetration and incomplete fusion can also be detected by penetrant examination if they are open to the surface. While undercut and overlap are readily detected by this method, they can usually be evaluated effectively using visual examination.

ELECTROMAGNETIC EXAMINATION

Electromagnetic examination methods, of which eddy current testing (described below) is an example, rely on the metal's interaction with electromagnetic fields created by specially designed probes or coils.

The components required for electromagnetic examination are a coil or coils carrying an alternating current, a means of measuring the electrical properties of the coil or coils, and a conductive specimen to be examined. The test coils are specialized sensing elements that are similar to the lenses in an optical system. Their design is a fundamental consideration depending upon the nature of the test. Probe coils, which are placed in contact with the surface to be examined, are used for the examination of a variety of metallic shapes for discontinuities. On the other hand, annular coils, which encircle the workpiece, are used especially for the examination of tubing, rods, bars, wires, and small parts.

Theory and Procedures

Electromagnetic examination involves (1) interaction between applied and induced electromagnetic fields, and (2) the imparting of energy into the test piece (much like the transmission of X-rays, heat, or ultrasound). Upon entering the test piece, a portion of the electromagnetic energy produced by the test coil is absorbed and converted into heat through the action of resistivity and, if the conductor is magnetic, hysteresis. The remainder of the energy is stored in the electromagnetic field. As a result, the electrical properties of the test coil are altered by the properties of the workpiece being examined. Hence, the current flowing in the coil reflects certain information about the workpiece, namely, dimensions; mechanical, metallurgical, and chemical properties; and the presence of discontinuities. The character of the interaction between the applied and induced electromagnetic fields is determined by two distinct phenomena within the test part. These are (1) the induction of eddy currents in the metal by the applied field and (2) the action of the applied field upon the magnetic domains, if any, of the workpiece.

Obviously, only the first phenomenon can act in the case of nonferromagnetic metals. In the case of ferromagnetic metals, both phenomena are present; however, the second usually has the stronger influence. This accounts for the basic difference in principle between the testing of ferromagnetic and nonferromagnetic metals.

Among the physical and metallurgical variables that affect electromagnetic tests in metals are the following:

1. Physical shape, external dimensions, and the thickness of the workpiece;
2. Distance between the workpiece and the electromagnetic coil;
3. Plating or coating thickness, if present;
4. Chemical composition;
5. Distribution of alloying or impurity elements (influenced by heat treatment of the workpiece);
6. Lattice dislocations caused by mechanical working;
7. Temperature;
8. Inhomogeneities and most types of discontinuities;
9. Residual and applied stresses in ferromagnetic metals;
10. Electrical conductivity of the metal; and
11. Magnetic permeability of the metal.

In practice, many (and sometimes all) of the above factors may vary simultaneously. Under such conditions, it is difficult to obtain a meaningful response from the magnetic flux set up within the test piece because several variables may have affected the test signal. Because of the above factors, standards that duplicate the examination conditions need to be evaluated.

The resulting voltage, which is the variable usually sensed by electromagnetic examination devices, must be very carefully analyzed to isolate the pertinent effects from any extraneous effects. Electromagnetic signals exhibit three important and measurable attributes—amplitude, phase, and frequency. They may contain either a single frequency (that selected for the examination) or a multitude of frequencies (harmonics of the signal frequency). In the latter case, the signal frequency is referred to as the *fundamental frequency*. In addition, amplitude and phase factors are associated with each harmonic frequency. The engineer utilizes a number of techniques that make use of all this information, thereby permitting discrimination between examination variables. Important parameters include amplitude discrimination, phase discrimination, harmonic analysis, coil design, frequency, and the degree of magnetic saturation.

Calibration and Quality Standards

When using electromagnetic methods for the examination of metals, it is essential that calibration standards be available to ensure the equipment is functioning properly and ascertain whether the discontinuities are cause for the rejection of the workpiece.

It is important to note that the discontinuity itself is not detected by the examination medium but rather the effect it has on the eddy currents in the workpiece being examined. It is therefore necessary to correlate the change in eddy currents with the cause of the change. For this reason, calibration standards in the form of prototypical specimens must be available when calibrating an electromagnetic examination unit. These specimens must contain either natural or artificial imperfections that can accurately reproduce the exact change in electromagnetic characteristics expected when production items are examined. Such standards are usually considered equipment calibration standards as they demonstrate that the equipment is sensing the discontinuities for which the piece is being examined. These specimens are used not only to facilitate the initial adjustment or calibration of the test instrument but also to check periodically the reproducibility of the measurements.

In addition to locating any discontinuities that may be present in the test specimen, the technician must also determine whether the discontinuities are severe enough to be cause for rejection. For this purpose, quality assurance standards are required against which the examination instrument can be calibrated to demonstrate the limits of acceptability or rejectability for all types of discontinuities.

Quality assurance standards take the form of actual production items that represent the limits of acceptability or prepared samples containing artificial discontinuities. The types of reference discontinuities that must be used for a particular application are generally detailed in the product specification. Among the discontinuities that have been used for reference standards are filed transverse notches, milled or electrical-discharge-machined longitudinal and transverse notches, and drilled holes.

Eddy Current Examination

Eddy current examination (ET) is a particular type of electromagnetic examination method in which eddy current flow is induced in the test specimen. Changes in the flow of the eddy currents caused by variations in the test piece or discontinuities in a weld are detected by a nearby coil or coils and measured by suitable instruments.

Eddy current examination is used primarily for the continuous inspection of seamless and welded piping and tubing during production. The examination of ferromagnetic steel, austenitic stainless steel, copper alloy, and nickel alloy tubular products is covered by ASTM specifications. It is important to note, however, that the examination results can be affected by disparities in the dimensions of the test specimen or the examination arrangement and by variations in the physical and metallurgical properties of the specimen.

Theory and Procedures. Eddy currents are circulating alternating electromagnetic currents induced in a conducting material by an adjacent alternating magnetic field. Generally, the currents are induced in the test specimen by making it the core of an alternating-current induction coil, as shown in Figure 14.35. A crack in a

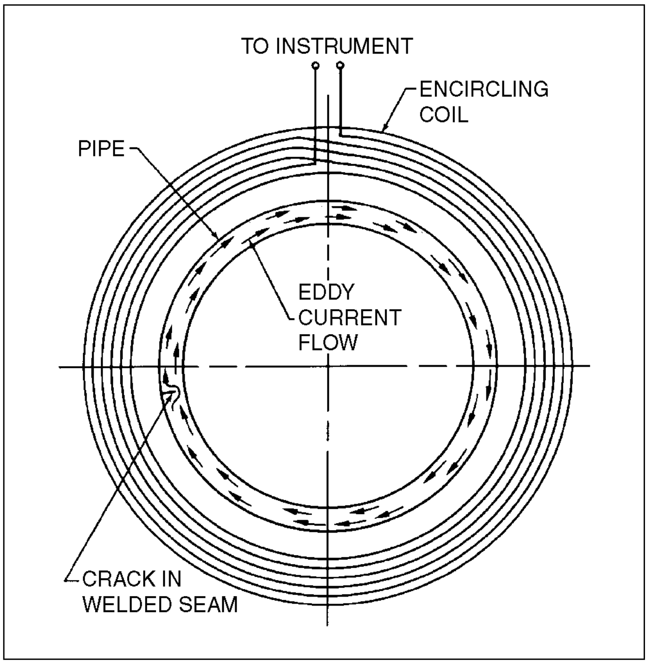


Figure 14.35—Effect of a Crack on an Eddy Current Flow during an Eddy Current Examination

welded seam disrupts the flow of the eddy currents and the magnetic field produced by these currents.

Two measurable changes occur in the magnitude and distribution of eddy currents. These are the resistive component and the inductive component of the exciting coil or a secondary coil. When measured separately, their combined influence results in an electrical property known as *impedance*. Electronic equipment is available for the measurement of these components.

The current distribution within a test specimen is changed if the specimen is not homogeneous. If the specimen is homogeneous and free from discontinuities and has an undistorted grain structure, the mean free path of an electron passing through is maximum in length. However, the presence of a crack, inclusion, cavity, or other conditions in an otherwise homogeneous material causes a backscattering of the electron flow, thereby shortening the electrons' mean free paths. This phenomenon allows the discontinuity to be indicated by the eddy currents.

When an energized coil is brought near a metal object, eddy currents are induced into the piece. Those currents set up magnetic fields that act in opposition to the original magnetic field. The impedance, Z, of the exciting coil or any coil in close proximity to the specimen is affected by the presence of the induced eddy currents in the object. When the path of the eddy currents in the object is distorted by the presence of discontinuities (see Figure 14.36), the apparent impedance of the coil is altered. This measurable change in impedance provides indications of discontinuities.

To a large extent, the coil used to induce the eddy currents determines the information that can be obtained during the examination. The basic electrical variables of an eddy current system are the alternating-current voltage, E, the current flowing through the coil, I, and the coil impedance, Z, which are related by the following equation:

$$I = \frac{E}{Z} \tag{14.1}$$

The impedance of the coil is affected by its magnetic field. Any changes in that field affect the current flow in the coil. The distance between the coil and the test piece also affects the impedance of the coil and the flow of the eddy current. This distance must be held constant to permit the detection of discontinuities in a moving test piece.

Impedance changes also affect the phase relationships between the voltage across the coil and the current through the coil. This provides a basis for sorting out the effects of the variations in spacing and other variables. Phase changes can be observed by means of a cathode ray tube or other display.

In generating eddy currents, the test object is brought into the field of a coil carrying alternating current. The coil may encircle the specimen, or it may be in the form of a probe. In the case of tubular shapes, the coil may be wound to fit inside the tube or pipe. Typical applications are shown in Figure 14.37.

The eddy current present in the metal object also sets up a magnetic field that opposes the original magnetic field. The impedance of the exciting coil or of a second coil coupled to the first and in close proximity to the test specimen is affected by the presence of the induced eddy currents. A second coil, referred to as a *sensing* or *pick-up coil,* is often used as a convenience.

In the case of a crack or an unwelded joint, the discontinuity must be oriented nearly perpendicular to the eddy current flow to disturb it. As the change in coil impedance caused by the presence of a discontinuity can be measured, it is used to provide an indication of the extent of defects. Subsurface discontinuities can also be detected, but the intensity of the eddy currents decreases with increasing depth.

Eddy currents are strongest near the surface of the test object. This phenomenon, termed the *skin effect*, is demonstrated in Figure 14.37. The term *standard depth* refers to that depth at which density of the eddy current is approximately 37% of that at the surface. The depth

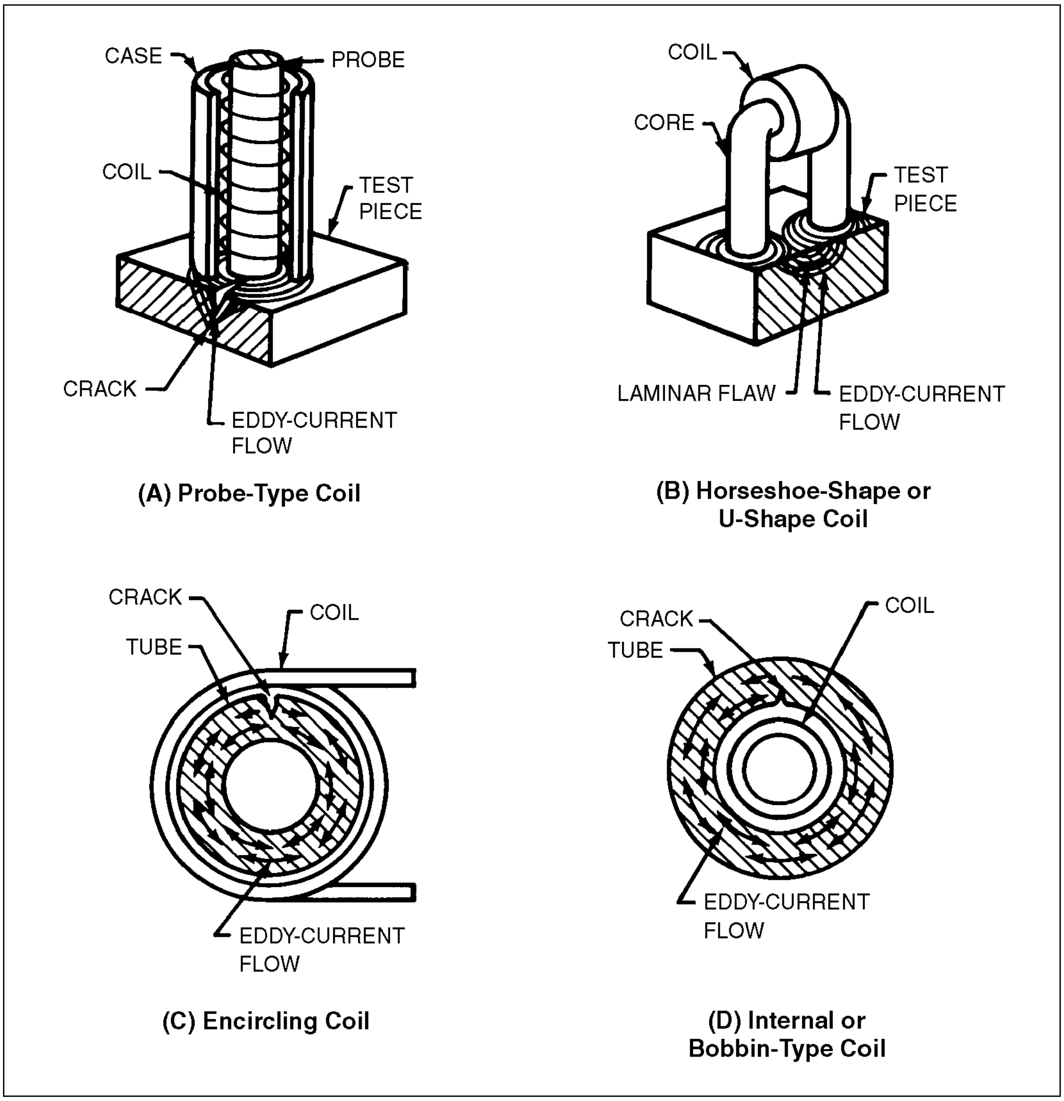


Figure 14.36—Types and Applications of Coils Used in Eddy Current Examination

of penetration of the current varies inversely with the electrical conductivity and magnetic permeability of the metal and with the frequency of the alternating eddy currents. Table 14.7 presents typical standard depths of penetration for several metals and magnetizing current frequencies. Normally, a workpiece being examined must have a thickness of at least two or three times the standard depth before thickness ceases to have an effect on eddy current response.

Advantages and Limitations. Any discontinuity that appreciably alters the normal flow of eddy currents can be detected by eddy current examination. Surface discontinuities that have a combination of predominantly longitudinal and radial dimensional components are readily detected with encircling-coil examination of either solid cylinders or tubes. When discontinuities of the same size are located at a progressively greater depth beneath the surface of the workpiece being examined, they become increasingly more difficult to detect. Discontinuities can be detected at depths greater than 1/2 in. (13 mm) only with special equipment designed for this purpose.

Laminar discontinuities, such as those sometimes found in welded tubes, may not sufficiently alter the flow of the eddy currents to be detected. These are

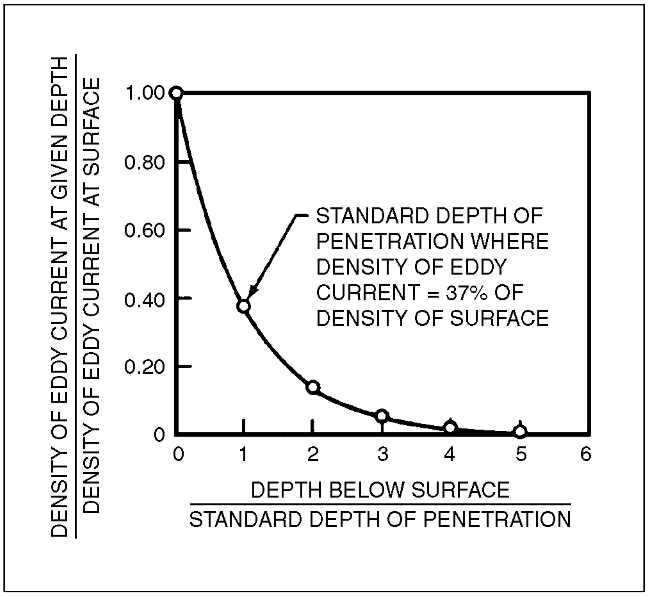


Figure 14.37—Variation in Eddy Current Density as a Function of Depth

detected in cases in which the discontinuity extends to the outside or inside surface or exists in a weld with outwardly bent fibers, caused by upsetting during welding. A similar difficulty could arise for the detection of a thin planar discontinuity that is oriented nearly perpendicular to the axis of the cylinder.

An important limitation of eddy current examination is that highly trained operators are required to calibrate the equipment, perform examinations, and interpret results. Moreover, any magnetic or electrically conductive surface contamination on the test specimen must be removed, as this may affect test results.

Regardless of the limitations of the eddy current examination technique, the majority of objectionable discontinuities can be detected at high travel speed and low cost. The discontinuities that are readily detected include seams, laps, cracks, slivers, scabs, pits, slugs, open welds, missed welds, misaligned welds, black or gray oxide weld penetrators, and porosity. This method is readily automated and can be used to examine any material that is electrically conductive.

ACOUSTIC EMISSION TESTING

Acoustic emission testing (AET) consists of the detection of acoustic signals produced during the loading or thermal stressing of materials. These signals are present in a wide-frequency spectrum along with ambient noise from many other sources. Transducers, which are strategically placed on a structure, are activated by incoming acoustic signals.

Applications

Acoustic emission examination is used to assess weld quality by monitoring the acoustic emissions from a weldment during and after welding, or both. Acoustic emissions are produced by numerous factors. These include plastic deformation, melting, friction, solidification, solid-phase transformation, and cracking. Regions having incomplete penetration, cracking, porosity, inclusions, or other discontinuities can be identified by detecting the acoustic emissions that originate in these regions.

Table 14.7
Typical Depths of Eddy Current Penetration with Magnetizing Current Frequency

	Standard (37%) Depth of Penetration											
	1 kHz		2 kHz		16 kHz		64 kHz		250 kHz		1000 kHz	
Metal	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Aluminum, Type 6061 T6	0.126	3.2	0.063	1.6	0.032	0.8	0.016	0.4	0.008	0.2	0.0040	0.1
Aluminum, Type 7075 T6	0.144	3.6	0.072	1.8	0.036	0.9	0.018	0.5	0.009	0.2	0.0046	0.1
Copper	0.082	2.1	0.041	1.0	0.021	0.5	0.010	0.3	0.005	0.1	0.0026	0.07
Lead	0.292	7.4	0.146	3.7	0.073	1.9	0.037	0.9	0.018	0.5	0.0092	0.2
Magnesium	0.134	3.4	0.066	1.7	0.033	0.8	0.017	0.4	0.008	0.2	0.0042	0.1
Stainless steel, Type 304	0.516	13.1	0.257	6.5	0.130	3.3	0.065	1.7	0.031	0.8	0.0165	0.4
Zirconium	0.445	11.3	0.222	5.6	0.112	2.8	0.056	1.4	0.028	0.7	0.0141	0.4
High-alloy steel*	0.020	0.5	0.0095	0.2	0.0049	0.1	0.0025	0.6	0.001	0.03	0.0006	0.01

*For depths without magnetic saturation. When ferromagnetic steels are saturated, their values are approximately the same as those for austenitic stainless steel.

The monitoring of acoustic emissions during welding can also include automatic feedback control of the welding process. In large-scale automatic welding, read-out equipment can be conveniently located near the welding controls or in a quality-monitoring area.

Procedure

The equipment used in acoustic emission examination typically consists of sensors, electronic instrumentation, and recording devices. The monitoring of acoustic emissions during welding may also require specialized apparatus because of severe environmental factors and interfering noise sources.

Figure 14.38 depicts a basic configuration for AET. Ambient noise in the composite signal is significantly reduced by suitable filtering methods. Any source emitting significant signals is located by triangulation based on the arrival times of these signals at several strategically placed transducers.

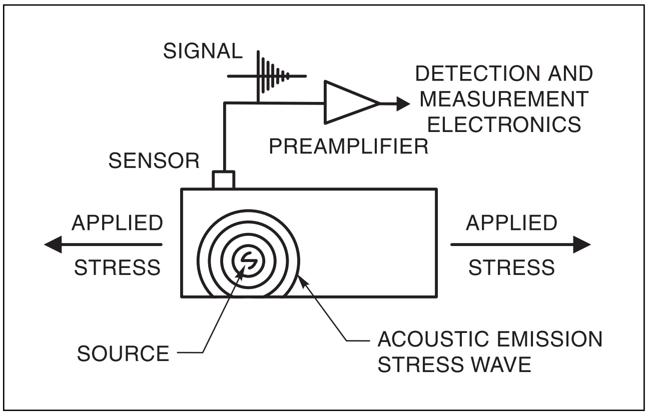
The publication *Standard Practice for Acoustic Emission Monitoring during Continuous Welding*, ASTM E 749[29] provides information regarding the performance of acoustic emission examinations. Additional information is provided in *Nondestructive Examination,* Section 5 of the *Boiler and Pressure Vessel Code*.[30] Information that should be included in written inspection procedures is discussed below.

Position of Acoustic Sources. The positions of acoustic sources along a welded joint can be displayed in a variety of ways. One technique displays the number of events versus distance along the weld on an oscilloscope screen or an X-Y plotter. Another technique utilizes a digital-line printer that provides the time of the event, its location, and its intensity. This information facilitates the appraisal of the severity of each source.

After the acoustic emission sources are graded, other nondestructive examination methods can be used to evaluate the indications.

Monitoring During Continuous Welding. Acoustic emission monitoring for the evaluation of quality and the control of a welding process requires preliminary studies for each application to establish operating conditions. These include the number, location, and mounting of sensors; gain settings; filtering; data presentation; and data interpretation. These studies normally include correlation with other nondestructive and destructive methods of examination.

29. American Society for Testing and Materials (ASTM) Subcommittee E07.04, *Standard Practice for Acoustic Emission Monitoring during Continuous Welding*, ASTM E 749-96, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
30. See Reference 22.



Source: Adapted from Pollock, A. A., 1989, Acoustic Emission Inspection, in *Nondestructive Evaluation and Quality Control*, Vol. 17 of *ASM Handbook*. 9th ed., Metals Park, Ohio: ASM International, Figure 1.

Figure 14.38—Schematic of Typical Arrangement for Acoustic Emission Examination

Acoustic emission activity from discontinuities in the weldment is stimulated by the thermal stresses produced during the welding process. The resulting activity is detected by sensors in the vicinity of the weld that convert the acoustic signals into electronic signals.

Acoustic emission data can be accumulated during the welding process. However, because of the delay between weld fusion and acoustic emission activity, monitoring must continue for some time following welding to acquire all significant data. Postweld monitoring time increases with increasing weld heat input, ranging from 10 seconds for manual gas tungsten arc welding (approximately 100 A) to more than 2 minutes for submerged arc welding (600 A to 800 A). The time should be established during developmental monitoring of trial welds. Observable conditions that occur in conjunction with unusual acoustic emission activity are recorded to aid the subsequent interpretation of the data. These conditions would include cleanup and chipping and grinding, for example.

In general, acoustic emission weld data must be evaluated against a baseline obtained from (1) known acceptable welds of a given type using the specific acoustic emission system and (2) signals from the same weld type known to contain defects. Significant weld discontinuities are characterized by increases in the acoustic emission event count, the rate of events, the intensity of the emission, or the peak amplitude.

Monitoring During Proof Testing. Acoustic emission examination methods are also applied to welded pressure vessels and other welded structures during proof testing. A sound vessel ceases to emit signals when the test load is reduced. It does not emit further bursts until the previous load has been exceeded. A growing crack continues to emit signals as it is loaded.

The location of suspect areas in such structures is a well-established acoustic emission examination technique. Some locating systems provide a sophisticated analysis of the signal data collected.

Recording of Results

With any type of examination, defective areas in a weldment must be identified in such a way as to assure that they will properly be located and repaired. Many identification methods are available. In addition to logging the results by type, size, and location, the defective area should be marked directly on the weldment. The following guidelines should be observed:

1. Appropriate personnel should be familiar with the marking system;
2. Marking should be positive, clear, and in a color that contrasts with the metal;
3. The color used to mark defects should not be used on the weldments for any other purpose;
4. The marking material must withstand exposure to handling or further processing until the defective area can be repaired but should not damage the weldment during subsequent processing or repair.

After the repair has been completed, the same inspection should be repeated, and the results should be carefully recorded.

Advantages and Limitations

The detection and location of acoustic emission sources in weldments during fabrication provides information about the integrity of welds. This information is used to direct repair procedures on the weld or guide the application of other NDE methods. A major attribute of acoustic emission examination for the in-process monitoring of welds is the ability of the method to provide real-time information on weld integrity. This feature promotes the lowering of welding costs by pinpointing defects that can be repaired at the most convenient point in the production process.

While acoustic emission examination is a valuable global inspection technique, it cannot normally provide quantitative data. Thus, subsequent inspection must be conducted with another nondestructive examination method. Additionally, the interpretation of results becomes complicated due to the presence of extraneous "noise" or acoustic emissions.

PROOF TESTING

Many welded components are nondestructively examined by means of proof testing during or subsequent to fabrication. Proof testing is performed by implementing one or more tests that exceed actual service requirements by a predetermined factor of safety. This may involve overloading the component or leak testing, or both. Proof testing is conducted to ensure safe operation, detect any design weakness, reveal quality deficiencies, and prevent in-service failures. Various proof testing methods are described below.

Load Testing

Welded components can be proof tested by applying specific loads without causing failure or permanent deformation. Such tests are usually designed to subject the parts to stresses exceeding those anticipated during service but not beyond those for which the weldment was designed. Many load test requirements and application details are mandated by codes, specifications, and contractual documents that apply to individual product forms.

Structural members are often proof tested by demonstrating their ability to carry loads equal to or larger than anticipated service conditions. This can be accomplished by statically loading with a testing machine, by using sandbags or scrap iron, or by dynamically loading with special testing equipment. Acceptance is based on the absence of cracking or objectionable permanent deformation.

Hydrostatic Testing

Closed containers are usually proof tested by filling them with water and applying a predetermined test pressure. For components built in accordance with the ASME *Boiler and Pressure Vessel Code*,[31] this pressure is often 150% of the design pressure. After a fixed holding time, the container is inspected for soundness by visually checking for leakage or monitoring the hydrostatic pressure. Visual inspection can be enhanced with an indicating system that is applied to the outside of the vessel. An example of an indicating system is light blue chalk that turns dark blue in the presence of a small amount of water. An enhancing material such as a water-soluble colored or fluorescent dye can be added to the test water for the detection of small leaks by developers or ultraviolet light. Open containers (e.g., storage tanks) can also be hydrostatically tested by filling them with water or partially submerging them in water, as is done with ship barges, for example. The

31. See Reference 22.

hydrostatic pressure exerted against any boundary is governed by the head of water.

Hydrostatic testing is a relatively safe operation because water is practically noncompressible and therefore stores little energy. A small leak results in a meaningful pressure drop that limits the driving force available to propagate a crack. However, three factors must be considered to ensure a safe hydrostatic test. First, the foundation and the support structure must be strong enough to hold the water-filled container. This is of special importance if the containers are designed to hold a gas or a lightweight liquid. The existence of any pockets where energy can build up in the form of compressed air should also be ascertained, and the air should be vented out, if possible. In addition, the metal must be at a temperature that provides adequate notch toughness to ensure that a relatively small leak or discontinuity does not propagate into a catastrophic brittle fracture.

Pneumatic Testing

Pneumatic testing is similar to hydrostatic testing except that compressed air is used to pressurize a closed vessel and that low pressures are typically used. This type of test is used primarily for small units that can be submerged in water. The water provides a convenient leak indicator in the form of air bubbles and is an effective energy absorber in the event the container fails. Other applications include units mounted on foundations that are not able to support the weight associated with hydrostatic tests and vessels that may be harmed by water or another liquid or from which a liquid cannot be adequately removed. An example of the latter is a plate-fin heat exchanger designed for cryogenic service.

When implementing pneumatic tests, acceptance is based on the absence of leakage. Small leaks are seldom detected without some type of indicating device. When a unit cannot be submerged in water, a soap bubble test is an effective procedure. This involves spraying the unit with a soap or detergent solution and checking for bubbles. For special applications, sound detection devices that report and locate all but the smallest air leaks are available.

During pneumatic testing, large amounts of energy may be stored in compressed air or gas in a large volume or under high pressure or both. A small leak or rupture can easily grow into a catastrophic failure, thereby endangering adjacent life and property. Thus, all pneumatic testing should follow a written procedure and safety precautions for the product to be tested. Caution should be observed because the pressures applied during pneumatic tests can result in violent explosion if a failure occurs, as the compressed gas/air volume rapidly expands.

Spin Testing

Welded components that rotate in service can be proof tested by spinning them at speeds above their design values to develop the desired stresses from centrifugal forces. Visual and other nondestructive examinations as well as dimensional measurements are employed to determine the acceptability of these parts. Spin testing must be done in a safe enclosure in case the component should rupture.

Leak Testing

When freedom from leakage is of primary importance and a high-pressure test is not desirable or possible, a number of low-pressure leak testing techniques are available. All are based on filling a container with a product that has a low viscosity and the ability to penetrate very small openings. A low-pressure pneumatic test may be an acceptable leak test for containers designed to hold water or oil, for example.

Tracer gases such as helium are often used to increase the effectiveness and accuracy of leak tests. Leak detection instruments (calibrated sniffers) are used to detect the presence of the tracer gas escaping through any leaks in the vessel.

Vacuum Box Testing

Pressure leak testing requires the ability to pressurize one side and inspect from the other side of the component. This constitutes a limitation for components that cannot be pressurized. However, in these cases, a vacuum box test can be used. This involves coating a test area with a soap or detergent film and placing a gasketed transparent box over the area to be examined. After evacuating the box to a partial vacuum of not less than 2 psig (14 kPa), the inspector looks for any bubble formations that indicate the presence of a leak. For critical service, such as liquid natural gas tanks, vacuum levels as high as 8 psig (55 kPa) may be used.

Mechanical Stress Relief

Proof testing operations reduce the residual stresses associated with welding. In the as-welded condition, weldments have peak residual stresses equal to or slightly below the yield strength of the metal. When proof testing the weldments, the yield strength may be exceeded in highly stressed areas, and the metal will plastically deform if it has adequate ductility at ambient temperature. After the load is removed, the peak residual stresses in those areas are lower than the original stresses. This result tends to improve product reliability.

Hardness Testing

Hardness testing can be used by inspectors as a nondestructive test on a production test piece or as a destructive test if the method renders the specimen unusable as a result of the indentation produced. Three types of static hardness tests are commonly used to measure the effects of processing on metals and to control production quality. These are the Brinell, Rockwell, and Vickers hardness tests. These tests are based on the size of an indentation made with a particular indenter design under a specified load. The choice of method depends on the size and finish of the area to be tested, the composition and thickness of the test object, and the intended use of the object.[32]

In the case of carbon and alloy steels, an approximate relationship exists between the Brinell, Rockwell, and Vickers hardness numbers and between the hardness number and tensile strength. These data are presented in tabular form in *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A 370.[33]

With Brinell hardness testing, the approximate tensile strength in psi (MPa) of carbon and low-alloy steels is 500 times the hardness number. The Brinell test is commonly used for quality control in industry, but the impression it leaves is relatively large compared to that produced by the other testing methods. This test can therefore be used only to determine hardness in a relatively large area where the impression on the surface is not objectionable. When marking affects the intended use of the product, the Rockwell or Vickers tests, which produce small surface indentations, can be implemented. Because these methods can be applied to small or narrow areas, they are often used for survey work to locate variations in hardness across a weld.

For the welding inspector, the most important difference involves the size of the indenter or penetrator, which may range from a 0.4 in. (10 mm) diameter ball to a small diamond tip. Although the size of the indenter has little effect on the test results for reasonably homogenous base or weld metal, it is of major importance when testing a narrow heat-affected zone or weld bead that contains several metallurgically differing zones. A small indenter may detect narrow areas of different hardness, while the 0.4 in. (10 mm) ball produces an average value for the entire zone. Any specification requirement that includes heat-affected zone hardness tests should specify the type of test (e.g., the Knoop test) and the indenter to be employed.

In hardness testing, proper specimen preparation is important for reliable results. The surface should be flat and reasonably free from scratches. It must also be normal to the applied load for uniform indentations. With thin, soft metals, the testing method must produce a shallow indentation that is not restricted by the anvil of the testing machine. This can be accomplished (particularly with a Rockwell testing machine) with a small indenter and a light load.

Brinell Hardness Test. The Brinell hardness test consists of impressing a hardened-steel ball into the test surface using a specified load for a definite time. Following this, the diameter of the impression is accurately measured and converted to a hardness number from a table. Stationary machines impress a 0.4 in. (10 mm) ball into the test object. The load for steel is 6600 pound-force (lbf) (3000 kilograms [kg]), whereas it is 1100 lbf or 3300 lbf (500 kg or 1500 kg) for softer metals. Two measurements of the impression diameters are taken at 90° from one another using a special Brinell microscope. The mean diameter is used to determine the Brinell hardness number from the table.

To test larger components, portable Brinell equipment consisting of a 0.3 in. or 0.4 in. (7 mm or 10 mm) ball and a calibrated reference bar is available. A hammer blow is used to indent both the reference bar and the material being tested simultaneously. The hardness of the material being tested can be determined by using a special slide rule or inserting the hardness of the reference bar and the diameters of the two indentations into a formula. The accuracy of this method is enhanced by selecting a reference bar of approximately the same hardness as the unknown test material. Examination should be performed according to the requirements of *Standard Test Method for Brinell Hardness of Metallic Materials,* ASTM E 10.[34]

Rockwell Hardness Test. The Rockwell hardness test measures the depth of residual penetration made in the specimen by a small hardened-steel ball or a diamond cone. The test is performed by applying a minor load of 22 lbf (10 kg) to seat the penetrator in the surface of the specimen and hold it in position. The machine dial is turned to a set point, and a major load is applied. After the pointer comes to rest, the major load is released, while the minor load remains.

The Rockwell hardness number is read directly on the dial. Hardened-steel balls of 1/8 in. or 1/16 in. (3.2 mm or 1.6 mm) diameter are used for soft metals, whereas a cone-shaped diamond penetrator is used for hard metals. Testing is conducted in accordance with

32. For additional information on these testing methods, see Chapter 6, "Test Methods for Evaluating Welded Joints."

33. American Society for Testing and Materials (ASTM) Subcommittee A01.13, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A 370, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

34. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Method for Brinell Hardness of Metallic Materials,* ASTM E 10, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials, ASTM E 18.[35]

Vickers Hardness Test. The Vickers hardness test is an indentation test that measures a metal's resistance to deformation. In this test, a square-based diamond indenter is impressed into the surface of the specimen under a predetermined load. The diagonals of the square impression are measured and averaged, providing a hardness value. Testing is conducted in conformance to *Standard Test Method for Vickers Hardness of Metallic Materials,* ASTM E 92.[36]

METALLOGRAPHIC EXAMINATION METHODS

While not normally employed as part of a routine examination effort, certain conditions require additional detailed information related to the metallurgical characteristics of welds and their related effects on base materials. Information of this nature can be provided through the use of various metallographic examination methods. In general, these methods involve the preparation of a specific surface, often a weld cross section, followed by visual examination of that surface. These techniques can be applied to determine the following information:

1. Soundness of the weld joint,
2. Distribution of nonmetallic inclusions in the weld joint,
3. Number of weld passes,
4. Location and depth of weld penetration,
5. Extent of the heat-affected zone,
6. Metallurgical structure in the weld metal and heat-affected zones.

Metallographic examination involves the visual examination of a prepared surface using the unaided eye or some levels of magnification. This surface may simply be ground smooth, or additionally polished, depending on the nature of the examination. This may be followed by etching, typically with an acid. The etching of the surface reveals gross structure and weld bead configuration. Pores, cracks, and inclusions are better observed on a polished surface. These methods can be classified as either macroscopic or microscopic, depending on the amount of magnification used.

Samples are obtained by sectioning test welds or production control welds, including run-off tabs. They can be prepared by cutting, machining, or grinding to reveal the desired surface and subjected to further preparation as needed to reveal the desired structure. Prior to conducting metallographic examinations, the entire heat-affected zone created by any thermal cutting process used during sample preparation must be mechanically removed.

Procedures for the selection, cutting, mounting, and polishing metallographic specimens are presented in *Standard Practice for Preparation of Metallographic Specimens,* ASTM E 3.[37] Recommended chemical solutions for etching various metals and alloys and safety precautions for the handling of etching chemicals are provided in *Standard Practice for Microetching Metals and Alloys*, ASTM E 407.[38]

Macroscopic Examination

Macroscopic examination is a form of metallographic examination in which no or low magnification is employed. Typically, this type of examination is performed using magnifications of 10X or less to reveal the heterogeneity of metals and alloys. Typical applications of macroetching include the study of weld structure; the measurement of joint penetration; the dilution of filler metal by base metal; and the identification of the presence of slag, flux, porosity, and cracks in the weld and heat-affected zones. When macroscopic examination is used as an inspection procedure, sampling should be done in an early stage of manufacturing to permit corrective action to be taken if necessary.

Recommended solutions and procedures for macroetching are presented in *Standard Test Method for Macroetching Metals and Alloys,* ASTM E 340.[39] Caution must be observed in handling chemicals and mixing solutions. Many of these etchants are strong acids that require special handling and storage. In all cases, the

35. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials,* ASTM E 18, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
36. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Method for Vickers Hardness of Metallic Materials,* ASTM E 92, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
37. American Society for Testing and Materials (ASTM) Subcommittee E04.01, *Standard Practice for Preparation of Metallographic Specimens,* ASTM E 3, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
38. American Society for Testing and Materials (ASTM) Subcommittee E04.01, *Standard Practice for Microetching Metals and Alloys,* ASTM E 407, West Conshohocken, Pennsylvania: American Society for Testing and Materials.
39. American Society for Testing and Materials (ASTM) Subcommittee E04.01, *Standard Test Method for Macroetching Metals and Alloys,* ASTM E 340, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

various chemicals should be added slowly to the water or other solvent while stirring.

Sample preparation need not be elaborate. Any method that prepares a smooth surface with a minimum amount of cold work is satisfactory. Cross sections may be faced on a lathe or a shaper. The usual procedure is to take a roughing cut, followed by a finish cut with sharp tools. This should provide a smooth surface and remove cold work from prior operations. Grinding is usually conducted in the same manner using free-cutting wheels and light finishing cuts. When fine detail is required, the specimen should be polished with a series of metallographic papers.

After surface preparation, the sample is carefully cleaned with suitable solvents, as any grease, oil, or other residue causes uneven etching. Once cleaned, the surface of the specimen should not be touched or contaminated in any way.

Microscopic Examination

In examining for exceedingly small discontinuities or for metallurgical structure at high magnification, specimens are polished, etched, and examined by microscope to reveal the microstructure of the base metal, heat-affected zone, fusion zone, and weld metal. In this method, magnifications over 50X are utilized. These techniques are more typically performed by metallurgists than by inspectors.

INSPECTION OF BRAZED AND SOLDERED JOINTS

The inspection of a completed assembly or subassembly, the last step in the brazing operation, is essential to ensure satisfactory and uniform quality of a brazed unit. The design of a brazement is extremely important to the inspection operation. Whenever practical, the design should permit easy and adequate examination of completed joints. An intelligent choice of brazing processes, brazing filler metal, joint design, and cleaning methods also aids the inspection process. The examination method chosen to evaluate a final brazed component depends on its service requirements. In many cases, the inspection methods are specified by the user or by regulatory codes.

The testing and inspection of brazed joints can be conducted on procedure qualification test joints or finished brazed assemblies. Preproduction and quality samples are often used for purposes of comparison during production. These are sample specimens made during the development of the brazing procedure or samples taken from actual production. They demonstrate the minimum acceptable production quality of the brazed joint.

Brazed joints and completed brazements can be tested both nondestructively and destructively. The nondestructive examination methods that may be used include visual examination as well as liquid penetrant, radiographic, ultrasonic, and proof and leak testing. Destructive testing methods include metallographic examination and peel, tension, shear, and torsion tests.

CONCLUSION

This chapter describes the methods that are commonly employed for the examination of welds to verify their quality and soundness. Numerous techniques exist inasmuch as no single method is appropriate for all applications. The method applied must be thoroughly understood and properly executed to assure that valid results are obtained. As the information provided in this chapter is intended to serve as an overview of the topic of welding inspection and nondestructive examination, practitioners are encouraged to consult the sources cited in the Bibliography and Supplementary Reading List for additional information.

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CHAPTER 15

QUALIFICATION AND CERTIFICATION

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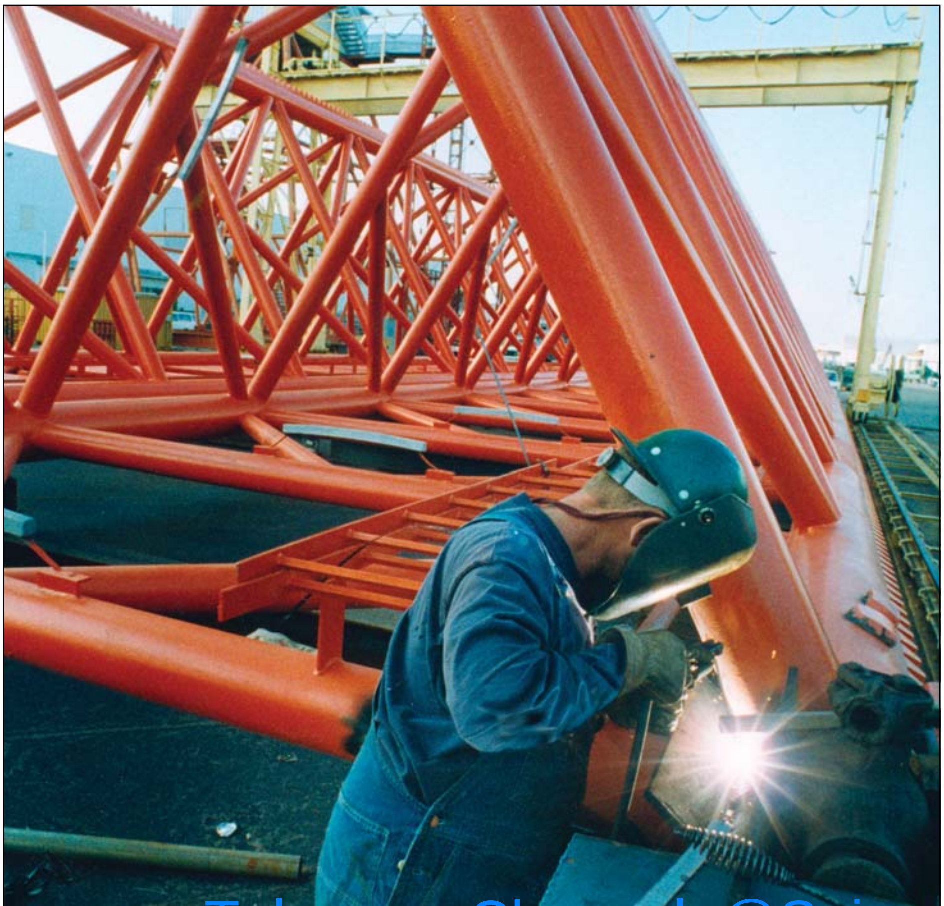


Photograph courtesy of Ingalls Shipbuilding

CHAPTER 15

QUALIFICATION AND CERTIFICATION

INTRODUCTION

To ensure that manufacturing processes and professionals render quality products and services, many local, state, and federal codes and regulations require the qualification and certification of fabrication procedures, inspection personnel, and engineering professionals. An example of one such regulation is the Occupational Safety and Health Administration's (OSHA) *Process Safety Management,* 29 CFR 1910.119, which requires that employers provide documentation of the qualifications of personnel in industries having recognized certification programs. Though this particular code is geared toward the chemical industry, it exemplifies the manner in which the federal government is becoming increasingly involved in qualification and certification. On the whole, government codes and regulations provide assurance that individuals are technically competent to perform work and provide inspection services in their industries.[1]

In the field of welding, qualification and certification programs are offered by organizations such as the American Welding Society (AWS) and the American Society for Nondestructive Testing (ASNT). In addition to their respective welding and welding-related qualification and certification programs, AWS and ASNT have embarked on a joint initiative to offer a certification program for inspection personnel. In the field of inspection, certification programs are offered by organizations such as AWS, ANST, and the National Board of Boiler and Pressure Vessel Inspectors. For example, the latter certifies Authorized Inspectors (AIs) in the local, state, and federal jurisdictions where the *National Board Inspection Code*[2,3] has been adopted as law. These authorized inspectors provide assurance that boilers and pressure vessels have been built, modified, or repaired in accordance with the requirements established by the National Board of Boiler and Pressure Vessel Inspectors and the American Society of Mechanical Engineers (ASME). Qualification and certification programs such as these have one main goal—to ensure that design practices, manufacturing processes, fabrication techniques, and inspection activities are performed by personnel who are qualified in accordance with good engineering practices and standards.

The qualification of welding procedures applies to all joining processes covered by a code or specification. These processes include arc welding (shielded metal arc welding [SMAW], gas tungsten arc welding [GTAW], and gas metal arc welding [GMAW]), oxyfuel gas welding (OFW), and other processes such as electron beam (EBW) and electroslag welding (ESW) and brazing (B). Each manufacturer is required to establish welding procedure specifications (WPSs) and brazing procedure qualifications (BPSs). These procedure specifications are the directions to be followed by the welder and brazer during the welding and brazing manufacturing processes. The manufacturer then demonstrates that the specification meets the standards required by the manufacturing

1. This chapter includes general discussions of the qualification and certification requirements specified by various codes and standards. These discussions should not be considered a substitute for reading and comprehending the actual governing codes or standards.

2. National Board of Boiler and Pressure Vessel Inspectors, *National Board Inspection Code*, NB-23, Columbus, Ohio: National Board of Boiler and Pressure Vessel Inspectors.

3. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

design and records the results of the testing of the weldment in the procedure qualification record (PQR).

Performance qualifications are normally required of personnel who perform manual, semiautomatic, and mechanized welding in production. Technical societies, trade associations, and government agencies have defined qualification requirements for welded fabrications in standards generally tailored for specific applications, such as buildings, bridges, cranes, piping, boilers, and pressure vessels. Most fabricating codes and standards require the qualification and certification of welding and brazing procedures and of the welders, brazers, and operators who perform welding and brazing operations in accordance with the procedures.[4]

Standards or contractual documents may also require that weldments or brazements be evaluated for acceptance by a qualified inspector. This evaluation may entail visual inspection or nondestructive examination of the weldments, or both. These activities are performed by qualified nondestructive examination personnel using the specified standardized testing procedures.

As the objectives of qualification are nearly the same in all codes and regulations, a welding procedure qualification performed in compliance with one standard may qualify the procedure for implementation under another standard provided the qualification test results meet the requirements of the latter. Moreover, some standards permit the acceptance of previous performance qualification by welders, brazers, and welding operators who present properly documented evidence of their certification.

The detailed document that specifies the required welding conditions for a specific application is referred to as a *welding procedure specification (WPS)*. The standard according to which the product is manufactured typically identifies which of the variables indicated in the welding procedure specification are qualification variables.[5] Should the qualification variables be modified beyond the specified limits, the welding procedure must be requalified. After requalification, a revised or new welding procedure specification is prepared.

Variables other than the qualification variables can be changed in the welding procedure specification without affecting the procedure's qualification status. However, all procedural changes require a revision of the welding procedure specification prior to the implementation of the revised procedure in production.

The welding procedure specification is normally qualified by demonstrating that the welded joints produced by means of the procedure meet the prescribed requirements. The welding conditions used to produce an acceptable test joint and the results of the qualification test are recorded on a form known as the *procedure qualification record (PQR)*.

Welders, brazers, and welding and brazing operators are normally required to demonstrate their ability to produce joints that meet the prescribed standards. This process is known as *performance qualification*. The results of weld procedure qualification and welder performance qualification must be certified by an authorized representative of the organization performing the qualification tests. This process is known as *certification*.

Listed below are several typical welding and brazing codes and specifications that require procedure or performance qualification:

Structural Welding Code—Steel, AWS D1.1;[6]
Structural Welding Code—Aluminum, ANSI/AWS D1.2;[7]
Structural Welding Code—Sheet Steel, ANSI/AWS D1.3;[8]
Structural Welding Code—Reinforcing Steel, ANSI/AWS D1.4;[9]
Bridge Welding Code, ANSI/AWS D1.5;[10]
Structural Welding Code—Stainless Steel, ANSI/AWS D1.6;[11]
Specification for Underwater Welding, ANSI/AWS D3.6;[12]
Sheet Metal Welding Code, ANSI/AWS D9.1;[13]

4. In the following discussion, the terms *weld, welder, welding,* and *welding operator* also imply *braze, brazer, brazing,* and *brazing operator*, respectively, unless otherwise noted.
5. Certain codes use the terms "essential variables" to denote qualification variables and "nonessential variables" to refer to all remaining WPS items. These codes include American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society; and American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, 1998, *Welding and Brazing Qualifications,* Section IX of the *1998 Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers.

6. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Steel,* AWS D1.1, Miami: American Welding Society.
7. American Welding Society (AWS) Structural Welding Committee, *Structural Welding Code—Aluminum,* ANSI/AWS D1.2, Miami: American Welding Society.
8. American Welding Society (AWS) Structural Welding Committee, *Structural Welding Code—Sheet Steel,* ANSI/AWS D1.3, Miami: American Welding Society.
9. American Welding Society (AWS) Structural Welding Committee, *Structural Welding Code—Reinforcing Steel,* ANSI/AWS D1.4, Miami American Welding Society.
10. American Welding Society (AWS) Structural Welding Committee, *Bridge Welding Code,* ANSI/AWS D1.5, Miami American Welding Society.
11. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Stainless Steel,* ANSI/AWS D1.6, Miami: American Welding Society.
12. American Welding Society (AWS) Committee on Welding in Marine Construction, Subcommittee on Underwater Welding, *Specification for Underwater Welding*, ANSI/AWS D3.6, Miami: American Welding Society.
13. American Welding Society (AWS) Committee on Structural Welding, *Sheet Metal Welding Code*, ANSI/AWS D9.1, Miami: American Welding Society.

Specification for Welding Industrial and Mill Cranes and Other Material Handling Equipment, ANSI/AWS D14.1;[14]
Specification for Metal Cutting Tool Weldments, ANSI/AWS D14.2;[15]
Specification for Earthmoving and Construction Equipment, ANSI/AWS D14.3;[16]
Specification for Welded Joints in Machinery and Equipment, ANSI/AWS D14.4;[17]
Specification for Welding of Presses and Press Components, ANSI/AWS D14.5;[18]
Specification for Welding of Rotating Elements of Equipment, ANSI/AWS D14.6;[19]
Railroad Welding Specification—Cars and Locomotives, ANSI/AWS D15.1;[20]
Welding and Brazing Qualifications, Section IX of the ASME *Boiler and Pressure Vessel Code*;[21]
National Board Inspection Code;[22] and
Welding of Pipelines and Related Facilities, API STD 1104.[23]

The codes and specifications listed above establish general requirements for welding procedure and performance qualification, with the exception of *Welding and Brazing Qualifications,* Section IX of the ASME *Boiler and Pressure Vessel Code*,[24] which addresses the essential and nonessential variables for welding and brazing procedure and performance qualification. Other standards address welding and brazing qualifications only. These may be referenced in contract documents or in the codes and specifications that do not address qualification. Examples of both follow:

Specification for Welding Procedure and Performance Qualification, ANSI/AWS B2.1;[25]
Standard for Brazing Procedure and Performance Qualification, ANSI/AWS B2.2;[26]
Standard for AWS Certification of Welding Inspectors, ANSI/AWS QC1;[27]
Standard for Accreditation of Test Facilities for AWS Certified Welder Program, ANSI/AWS QC4;[28]
Standard for AWS Certified Welders, AWS QC7;[29]
Guide for the Nondestructive Inspection of Welds, ANSI/AWS B1.10;[30] and
Guide for the Visual Examination of Welds, AWS B1.11.[31]

WELDING AND BRAZING PROCEDURE SPECIFICATIONS

Two types of welding procedure specifications are commonly used. The first type consists of broad, general procedures that apply to all welding of a given kind on a specific base metal or group of base metals. These broad procedures are usually advantageous to the manufacturer. They offer the flexibility of welding a greater number of base metals and filler metals with the same weld procedure within the limits of the code. The other type consists of a narrower, more definitive procedures that detail the welding of a single size and type of joint in a specific base metal or weldment. These procedure specifications are frequently used to control repetitive in-plant welding operations on a specific type of base metal and filler metal. They are also used by purchasers

14. American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Welding Industrial and Mill Cranes and Other Material Handling Equipment*, ANSI/AWS D14.1, Miami: American Welding Society.
15. American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Metal Cutting Tool Weldments,* ANSI/AWS D14.2, Miami: American Welding Society.
16. American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Earthmoving and Construction Equipment*, ANSI/AWS D14.3, Miami: American Welding Society.
17. American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Welded Joints in Machinery and Equipment,* ANSI/AWS D14.4, Miami: American Welding Society.
18. American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Welding of Presses and Press Components,* ANSI/AWS D14.5, Miami: American Welding Society.
19. American Welding Society (AWS) Committee on Machinery and Equipment, *Specification for Welding of Rotating Elements of Equipment,* ANSI/AWS D14.6, Miami: American Welding Society.
20. American Welding Society (AWS) Committee on Railroad Welding, *Railroad Welding Specification—Cars and Locomotives,* ANSI/AWS D15.1, Miami: American Welding Society.
21. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, *Welding and Brazing Qualifications,* Section IX of the *Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers.
22. See Reference 2.
23. American Petroleum Institute (API), *Welding of Pipelines and Related Facilities,* API STD 1104, Washington, D.C.: American Petroleum Institute.
24. See Reference 21.
25. AWS Committee on Welding Qualification, *Specification for Welding Procedure and Performance Qualification,* ANSI/AWS B2.1, Miami: American Welding Society.
26. AWS Committee on Welding Qualification, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2, Miami: American Welding Society.
27. AWS Qualification and Certification Committee, *Standard for AWS Certification of Welding Inspectors.* AWS QC1, Miami: American Welding Society.
28. AWS Qualification and Certification Committee, *Standard for Accreditation of Test Facilities for AWS Certified Welder Program,* AWS QC4, Miami: American Welding Society.
29. AWS Qualification and Certification Committee, *Standard for AWS Certified Welders,* AWS QC7, Miami: American Welding Society.
30. American Welding Society (AWS) Committee on Methods of Inspection, *Guide for the Nondestructive Examination of Welds,* ANSI/AWS B1.10, Miami: American Welding Society.
31. American Welding Society (AWS) Committee on Methods of Inspection, *Guide for the Visual Examination of Welds,* AWS B1.11, Miami: American Welding Society.

desiring specific metallurgical, chemical, or mechanical properties.

Either type of welding procedure specification may be acceptable to a customer or an agency, depending upon the nature of the welding involved and the judgment of those in charge. In addition, the two types are sometimes combined to varying degrees, with addenda to indicate the exact details for specific joints in addition to the broader, more general specification.[32]

Welding procedure specifications are sometimes required by the purchaser to govern the fabrication of a given product in an employer's[33] shop. More often, however, the purchaser specifies the properties desired in the weldment in accordance with a code or specification. The employer then develops a welding procedure that will produce the specified results.

In other cases, the purchaser, through contractual documents, may require special properties of welded joints because of a critical function of a particular weldment. In this case, the employer must either conduct additional tests that meet the selected construction code to prove that this practice meets the customer's requirements or prepare a new welding procedure specification and qualify it in accordance with the applicable code and contract requirements.

PROCEDURE SPECIFICATIONS FOR THE ARC WELDING PROCESSES

Many factors contribute to the product of an arc welding operation, whether this be the manual shielded metal arc welding of plain carbon steel or the gas metal arc welding of exotic heat-resistant alloys. It is always desirable and often essential to describe the vital elements associated with the welding of joints in sufficient detail to permit their reproduction and provide a clear understanding of the intended practices. The purpose of the welding procedure specification is to define in detail the variables involved in the welding of a certain base metal or combination of base metals. It also establishes parameters that consistently produce results that meet a predetermined engineering design. To fulfill this purpose efficiently, welding procedure specifications should be written as clearly as possible.

Organizations such as the American Welding Society publish standard welding procedures. It is important to note, however, that welding procedure specifications do not replace the fabrication codes, standards, or specifications to which a product is to be manufactured. Instead, they are intended as a guideline for the production of welds utilizing a specified list of variables.

Content

Codes and other standards generally require that the employer prepare and qualify welding procedure specifications. Some standards are very specific in defining the content to be included. They may list the specific variables to be addressed and specify which of these are qualification variables. Other codes refer only to the welding variables of a specific process that may affect qualification. In this case, the user determines which other variables and information should be included in the welding procedure specification.

As a rule, welding procedure specifications should list all the welding variables that may affect the mechanical properties of the weld and quality requirements. These include the welding process, welding technique, welding position, base metal, joint geometry, filler metal, preheat and interpass temperatures, welding current, arc voltage, shielding gas or flux, and postweld heat treatment. All arrangements and details indicated in welding procedure specifications must conform to the requirements of the contract and the purchasers as well as good industry practice. They should be sufficiently detailed to ensure that the welding satisfies the requirements of the applicable code, rules, and purchaser specifications.

Some fabrication codes permit the use of prequalified joint welding procedures. For example, *Structural Welding Code—Steel,* AWS D1.1:2000, permits prequalified status for a number of joint welding procedures as an alternative to the testing of each weld procedure by the manufacturers.[34] Under this system, the employer prepares a written procedure conforming to the specific requirements of that code for materials, joint design, welding technique, preheat, filler metal, and so on. Welding procedure qualification tests need not be performed as long as the specific requirements of the code are given to the welder in the welding procedure qualification. The manufacturer must also use good judgment in the application of the prequalified welding procedures and accept the responsibility for their use in construction.

32. Paragraph QW-200.4 of American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, 1998, *Welding and Brazing Qualifications*, Section IX of the *1998 ASME Boiler and Pressure Code*, New York: American Society of Mechanical Engineers allows for a manufacturer's weld procedures to be used in part or in combination with other weld procedures provided they are within the limits of each procedure (pp. 14–15). Paragraph 3.6.1 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society allows the combination of weld procedures provided that the allowable capacity is calculated.

33. In this chapter, every instance of the term *employer* refers to the manufacturer or contractor that produces the weldment for which welding procedures and performance qualifications are required.

34. American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society.

Deviations from these requirements negate the prequalified status and require qualification by testing.

The use of prequalified and qualified welding procedures does not guarantee satisfactory production welds or the ability of welders and welding operators to perform. The quality of production welds is sometimes verified by nondestructive examination, which is performed during and after welding. The results of this testing are reviewed in accordance with the construction code in use. Methods of welded joint examination include visual inspection, magnetic particle, liquid penetrant, ultrasonic, and radiographic testing.

Most codes permit an organization other than the employer's to prepare test coupons and specimens and perform the required nondestructive or destructive examination. However, each employer must supervise and control each welder or welding operator during the welding of the procedure qualification test coupons. The employer is also responsible for the technical accuracy of the welding procedure specifications and the performance qualification record as well as for ensuring that welding procedure specifications are followed during fabrication or construction.

Regardless of the differences between the welding procedure specification and the requirements of the fabrication standards, the welding procedure specification not only provides direction to the welder or welding operator but is also an important control document. It should have a specific identification number and an approval signature prior to its release for production welding. Responsibility for the content, qualification status, and use of welding procedure specifications rests with the employer, who may elect to delegate the authority to a responsible individual in the organization for the approval of a welding procedure specification, the certification of a performance qualification record, or the certification of a record of performance. The employer may also have a quality control program to provide this responsible individual direction with respect to establishing a welding procedure specification, qualifying a weld procedure, and certifying a welder's or welding operator's competency.

Typical items of content that may be specified in a welding procedure specification are discussed below. Not all of these necessarily apply to every process or application. In addition, not all variables present in certain welding processes are covered. In all cases, the applicable code or specification defines the specific requirements to be adhered to.

Scope. The welding processes, applicable base and filler metals, and other welding parameters must be clearly stated in the welding procedure specifications. ASME's *Welding and Brazing Qualifications*, Section IX of the *1998 Boiler and Pressure Vessel Code* is very explicit in describing the "essential," "nonessential," and "supplementary essential variables" required for this specification.[35] Table 15.1 presents a typical listing of these variables for shielded metal arc welding.[36] In this table, the paragraph and clauses listed in the first column correspond to the complete descriptions of the variables, which are shown in Article IV of the above-cited publication.

Base Metal. The base metal or group of base metals to be used must be listed in the welding procedure specification. ASME has assigned each base material a corresponding P-Number (P-No.) for identification purposes. These numbers are based on the chemical composition of the metal. If any special treatment of the base metal is required by specification before welding, this should be indicated. Such treatment could include heat treatment, cold working, and any type of cleaning or preparation required.

It is necessary to be explicit because a given base metal may not produce the same results when joined with a dissimilar base metal as it does when joined with a base metal of the same composition. Thus, the fabricator should identify the base metal, the type of preparation, and the thickness of the test piece required. Table 15.2 presents a typical grouping of base metals for qualification.

Welding Process. The type of welding process (or combination of welding processes that are to be used), whether this be shielded metal arc welding, gas metal arc welding, gas tungsten arc welding, oxyfuel gas welding (OFW), or plasma arc welding (PAW), must be stated in the welding procedure specification.

Filler Metal. The type of filler metal used to join the base metals must be specified by the manufacturer or fabricator. These filler metals are also classified by the American Welding Society and ASME according to their chemical composition and assigned a corresponding Filler Number (F-Number or F-No.). Filler metal marking is usually sufficient to identify the specified grade of metal being used.

The size of electrodes that may be used for base metals of different thickness or for different welding positions must be specified. Table 15.3 presents a listing of the grouping of electrodes and welding rods used for qualification.

35. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, 1998, *Welding and Brazing Qualifications,* Section IX of the *1998 Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers.

36. A similar table, Table QB-416, is presented in American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, 1998, *Welding and Brazing Qualifications,* Section IX of the *1998 Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers publication to specify brazing variables for brazer and brazing operator performance.

Table 15.1
Welding Variables Procedure Specifications (WPS)
Shielded Metal Arc Welding (SMAW)

Paragraph			Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-402 Joints	.1	ϕ	Groove design			x
	.4	−	Backing	x		
	.10	ϕ	Root spacing			x
	.11	±	Retainers			x
QW-403 Base metals	.5	ϕ	Group Number		x	
	.6		*T* limits impact		x	
	.7		*T/t* limits > 8 in. (203 mm)	x		
	.8	ϕ	*T* qualified	x		
	.9		*t* pass > 1/2 in. (13 mm)	x		
	.11	ϕ	P-Number qualified	x		
	.13	ϕ	P-Number 5/9/10	x		
QW-404 Filler metals	.4	ϕ	F-Number	x		
	.5	ϕ	A-Number	x		
	.6	ϕ	Diameter			x
	.7	ϕ	Diameter > 1/4 in. (0.25 mm)		x	
	.12	ϕ	AWS classification		x	
	.30	ϕ	*t*	x		
	.33	ϕ	AWS classification			x
QW-405 Positions	.1	+	Position			x
	.2	ϕ	Position		x	
	.3	ϕ	↑↓Vertical welding			x
QW-406 Preheat	.1		Decrease > 100°F (56°C)	x		
	.2	ϕ	Preheat maintenance			x
	.3		Increase > 100°F (56°C) (IP)		x	
QW-407 Postweld heat treatment (PWHT)	.1	ϕ	PWHT	x		
	.2	ϕ	PWHT (T & T range)		x	
	.4		*T* limits	x		
QW-409 Electrical characteristics	.1	>	Heat input		x	
	.4	ϕ	Current or polarity		x	x
	.5	ϕ	Current & voltage range			x
QW-410 Technique	.1	ϕ	String/weave			x
	.5	ϕ	Method cleaning			x
	.6	ϕ	Method backgouge			x
	.25	ϕ	Manual or automatic			x
	.26	±	Peening			x

Legend:

- ϕ = Change
- + = Add
- − = Delete
- > = Increase/greater than
- ↑ = Uphill
- ↓ = Downhill
- < = Decrease/less than
- *T* = Base metal thickness
- *t* = Deposited metal thickness
- P-Number = Base metal designation by Table QW-422 in *Welding and Brazing Qualifications*,* Section IX of the *1998 Boiler and Pressure Vessel Code*
- F-Number = Filler metal designation by Table QW-432 in *Welding and Brazing Qualifications*,* Section IX of the *1998 Boiler and Pressure Vessel Code*
- A-Number = Chemical analysis of filler metal defined by Table QW-442 in *Welding and Brazing Qualifications*,* Section IX of the *1998 Boiler and Pressure Vessel Code*
- T & T range = Time and temperature parameters
- IP = Interpass

*See Reference 35.

Source: Adapted from American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, *Welding and Brazing Qualifications*, Section IX of the *1998 Boiler and Pressure Vessel Code*, New York: American Society of Mechanical Engineers, Table QW-253.

Table 15.2
Typical Groupings of Base Metals for Welding and Brazing

QW-420.1 P-Numbers. To reduce the number of welding and brazing procedure qualifications required, base metals have been assigned P-Numbers, and for ferrous base metals that have specified impact test requirements, Group Numbers within P-Numbers. These assignments are based essentially on comparable base metal characteristics such as composition, weldability, brazeability, and mechanical properties, when this can logically be done. These assignments do not imply that base metals may indiscriminately be substituted for a base metal that was used in the qualification test without consideration of compatibility from the standpoint of metallurgical properties, postweld heat treatment, design, mechanical properties, and service requirements. When notch toughness is a consideration, it is presupposed that the base metals meet the specific requirements.

Base Metal	Welding	Brazing
Steel and steel alloys	P-Number 1 through P-Number 11, including P-Numbers 5A, 5B, and 5C	P-Number 101 through P-Number 103
Aluminum and aluminum-based alloys	P-Number 21 through P-Number 25	P-Number 104 and P-Number 105
Copper and copper-based alloys	P-Number 31 through P-Number 35	P-Number 107 and P-Number 108
Nickel and nickel-based alloys	P-Number 41 through P-Number 47	P-Number 110 through P-Number 112
Titanium and titanium-based alloys	P-Number 51 through P-Number 53	P-Number 115
Zirconium and zirconium-based alloys	P-Number 61 through P-Number 62	P-Number 117

Source: Adapted from American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, *Welding and Brazing Qualifications*, Section IX of the *1998 Boiler and Pressure Vessel Code*, New York: American Society of Mechanical Engineers, p. 69.

Type and Range of Current. Whenever welding involves the use of electric current, the type of current to be used must be specified. Some electrodes utilized in shielded metal arc welding can be used with either alternating current (ac) or direct current (dc). If dc is specified, the proper polarity must be indicated. The current range for each size of electrode, position, and thickness must also be indicated.

Arc Voltage and Travel Speed. For most arc welding processes, it is common practice to list an arc voltage range. Ranges for travel speed are mandatory for automatic and robotic welding processes and frequently mandatory for semiautomatic welding processes. If the properties of the base metal can be impaired by heat input, permissible limits for travel speed or width of weld bead are necessary.

Joint Design and Tolerances. Details regarding permissible joint design should be indicated in the welding procedure specification to serve as an example for a specific type of joint as well as for a sequence for welding. This information can be imparted by means of cross-sectional sketches showing the thickness of the base metal and details of the joint. As an alternative, reference can be made to the standard drawings that are published in some codes and standards, provided those drawings are available to the welder.

Joint and Surface Preparation. The methods to be used to prepare joint faces as well as the degree of surface cleaning required should be designated in the welding procedure specification. These methods may include oxyfuel gas, air-carbon arc, or plasma arc cutting, with or without surface cleaning. Surface preparation may involve blasting, machining, or grinding followed by vapor, ultrasonic, dip, or lint-free cloth cleaning. All methods and practices should conform to the application and metal.

Tack Welding. As tack welding can affect weld soundness, details concerning tack welding procedures should be included in the welding procedure specification. Tack welders must use the designated procedures and may be required to be qualified to perform such work. Most codes require that tack welders be qualified when the tack welds performed are incorporated into the final weld joint.

Welding Details. With respect to specification requirements, all details that influence weld quality should be clearly outlined in the welding procedure specification. These typically include the appropriate size of the electrode for different portions of the joint and different positions, the arrangement of weld passes for filling joints, and the limitations of the pass width or electrode weave. These details can influence the soundness of welds and the mechanical properties of finished joints.

Welding Positions. The welding procedure specification should always designate the positions in which

Table 15.3
Groupings of Electrodes and Welding Rods for Qualification

F-No.	AWS Specification	AWS Classification
		Steel
1	A5.1	EXX20, EXX22, EXX24, EXX27, EXX28
1	A5.4	EXX(X)-25, EXX(X)-26
1	A5.5	EXX20-XX, EXX27-XX
2	A5.1	EXX12, EXX13, EXX14, EXX19
2	A5.5	E(X)XX13-XX
3	A5.1	EXX10, EXX11,
3	A5.5	E(X)XX10-XX, E(X)XX11-XX
4	A5.1	EXX15, EXX16, EXX18, EXX18M, EXX48
4	A5.4 other than austenitic and duplex	EXXX(X)-15, EXXX(X)-16, EXXX(X)-17
4	A5.5	E(X)XX15-XX, E(X)XX16-XX, E(X)XX18-XX, E(X)XX18M(1)
5	A5.4 austenitic and duplex	EXXX(X)-15, EXXX(X)-16, EXXX(X)-17
6	A5.2	RX
6	A5.9	ERXXX(XXX), ECXXX(XXX), EQXXX(XXX)
6	A5.17	FXXX-EXX, FXXX-ECX
6	A5.18	ERXXS-X, EXXC-X, EXXC-XX
6	A5.20	EXXXT-X, EXXT-XM
6	A5.22	EXXXTX-X, RXXXT1-5
6	A5.23	FXXX-EXXX-X, FXXX-ECXXX-X
6	A5.23	FXXX-EXXX-XN, FXXX-ECXXX-XN
6	A5.25	FESXX-EXXX, FESXX-EWXX
6	A5.26	EGXXS-X and EGXXT-X
6	A5.28	ERXXS-X and EXXC-X
6	A5.29	EXXTX-X
6	A5.30	INXXXX
		Aluminum and Aluminum Alloys
21	A5.3	E1100, E3003
21	A5.10	ER1100, R1100, ER1188, R1188
22	A5.10	ER5183, R5183, ER5356, R5356, ER5554, R5554, ER5556, R5556, ER5654, R5654
23	A5.3	E4043
23	A5.10	ER4010, R4010, ER4043, R4043, ER4047, R4047, ER4145, R41455, ER4643, ER4643, R4643
24	A5.10	ER4009, R4009, R206.0, R-C355.0, R-A356.0, R-A357.0, R-A357.0, R4011
25	A5.10	ER2319, R2319
		Copper and Copper Alloys
31	A5.6 and A5.7	RCu, ECu
32	A5.6	ECuSi and ERCuSi-A
33	A5.6 and A5.7	EcuSn-A, EcuSn-C
34	A5.6, A5.7, and A5.30	ECuNi, ERCuNi, IN67
35	A5.8	RBCuZn-A, RBCuZn-B, RBCuZn-C, RBCuZn-D
36	A5.6 and A5.7	ERCuAl-A1, ERCuAl-A2, ERCuAl-A3, ECuAl-A2, EcuAl-B
37	A5.6 and A5.7	RCuNiAl, ECuMnNiAL, ERCuNiAl, ERCuMnNiAl

(Continued)

Table 15.3 (Continued)
Groupings of Electrodes and Welding Rods for Qualification

F-No.	AWS Specification	AWS Classification
		Nickel and Nickel Alloys
41	A5.11, A5.14, and A5.30	ENi-1, ErNi-1, IN61
42	A5.11, A5.14, and A5.30	ENiCu-7, ERNiCu-7, IN60
43	A5.11, A5.14, and A5.30	EniCrFe-1, -2, -3, and -4, EniCrMo-2, -3, -6, and -12, EniCrCoMo-1
		ERNiCrCoMo-1, ERNiCrMo-1, -2, and -3
		ERNiCr-3, ERNiCrFe-5 and -6
		IN82, IN62, IN6A
44	A5.11 and A5.14	ENiMo-1, -3, and -7, ERNiMo-1, -2, -3, and -7 (B2)
		EniCrCo-4, -5, -7, and -10, ERNiCrMo-4, -7 (alloy C4), and -10
45	A5.11	EniCrMo-1, -9, and -11
45	A5.14	ERNiCrMo-8, -9, and -11, ERNiFeCr-1
		Titanium and Titanium Alloys
51	A5.16	ERTi-1, -2, -3, and -4
52	A5.16	ERTi-7
53	A5.16	ERTi-9, ERTi-9ELI
54	A5.16	ERTi-12
55	A5.16	ERTi-5, ERTi-5ELI, ERTi-6, ERTi-6ELI, ERTi-15
		Zirconium and Zirconium Alloy
61	A5.24	ERZr2, ERZr3, and ERZr4
		Hardfacing Weld Metal Overlay
71	A3.13 and A5.21	RXXX-X, EXXX-X
		Magnesium Alloys
91	A5.19	ER AZ61A, ER AZ92A, ER EZ33A, ER AZ101A
		R AZ61A, R AZ92A, R AZ101A, R EZ33A

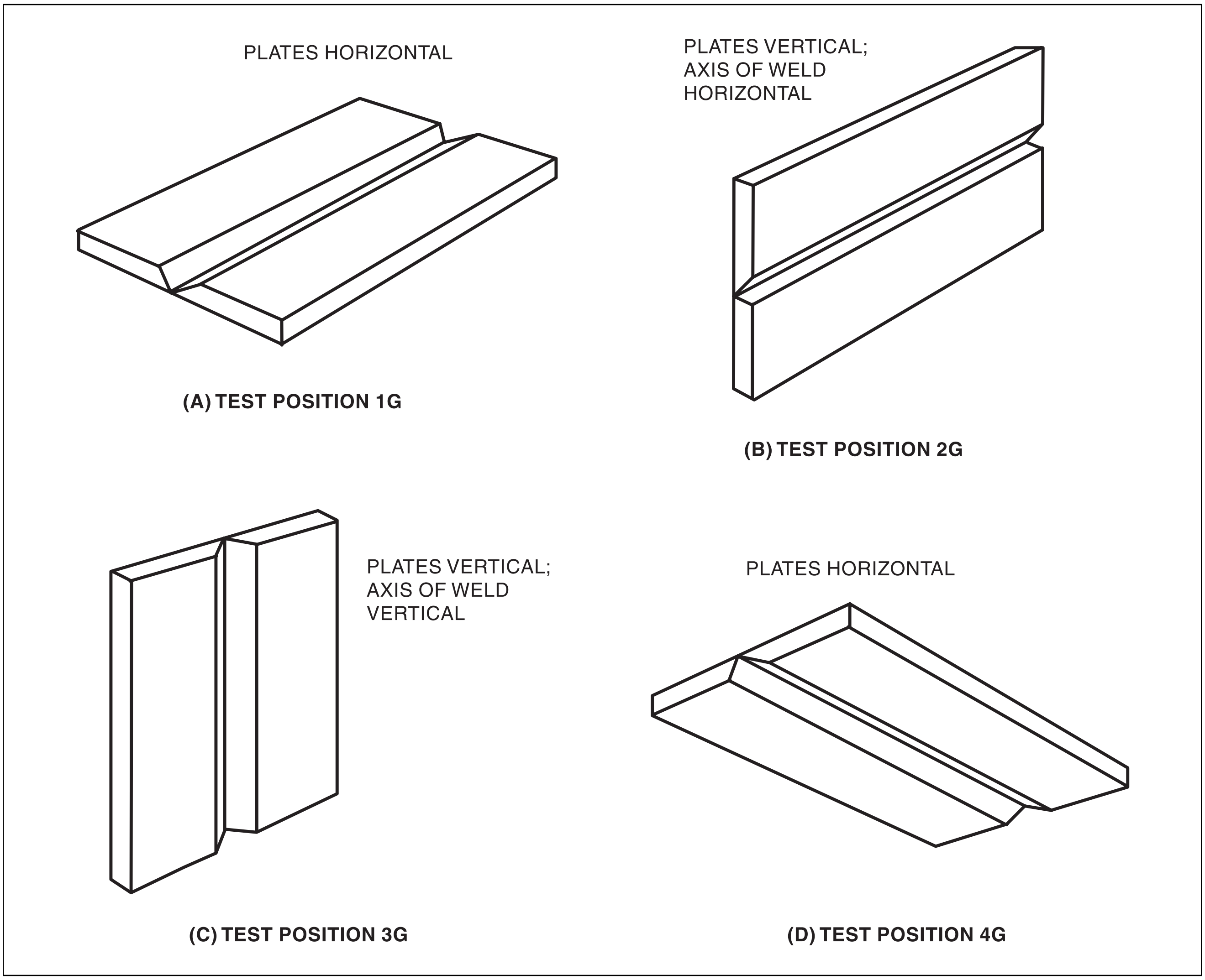
Source: AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society, Table C1.

welding can be accomplished. The manner in which the welding is to be performed in each position should be also designated. This information may include the electrode or torch size; the welding current range; the shielding gas flow; the thickness and arrangement of weld passes; the direction of travel; the travel speed; string or weave pass; the number of passes; and so forth.

Welding test positions 1G through 6G are illustrated in Figures 15.1 and 15.2. The defined limits or boundaries of each position for groove welds and fillet welds are shown in Figures 15.3 and 15.4, respectively.

Preheat and Interpass Temperatures. Whenever preheat or interpass temperatures are significant factors in the production of sound joints or influence the properties of welded joints, the temperature limits of both the joint and the base metals should be specified in the welding procedure specification. The preheat and interpass temperatures must often be kept within a well-defined range to avoid the degradation of the heat-affected zone in the base metal. The applicable construction code (e.g., *Process Piping*, ANSI/ASME B31.3[37]) should be referred to for the proper temperature ranges.

37. American Society of Mechanical Engineers (ASME), *Process Piping*, ANSI/ASME B31.3, New York: American Society of Mechanical Engineers.



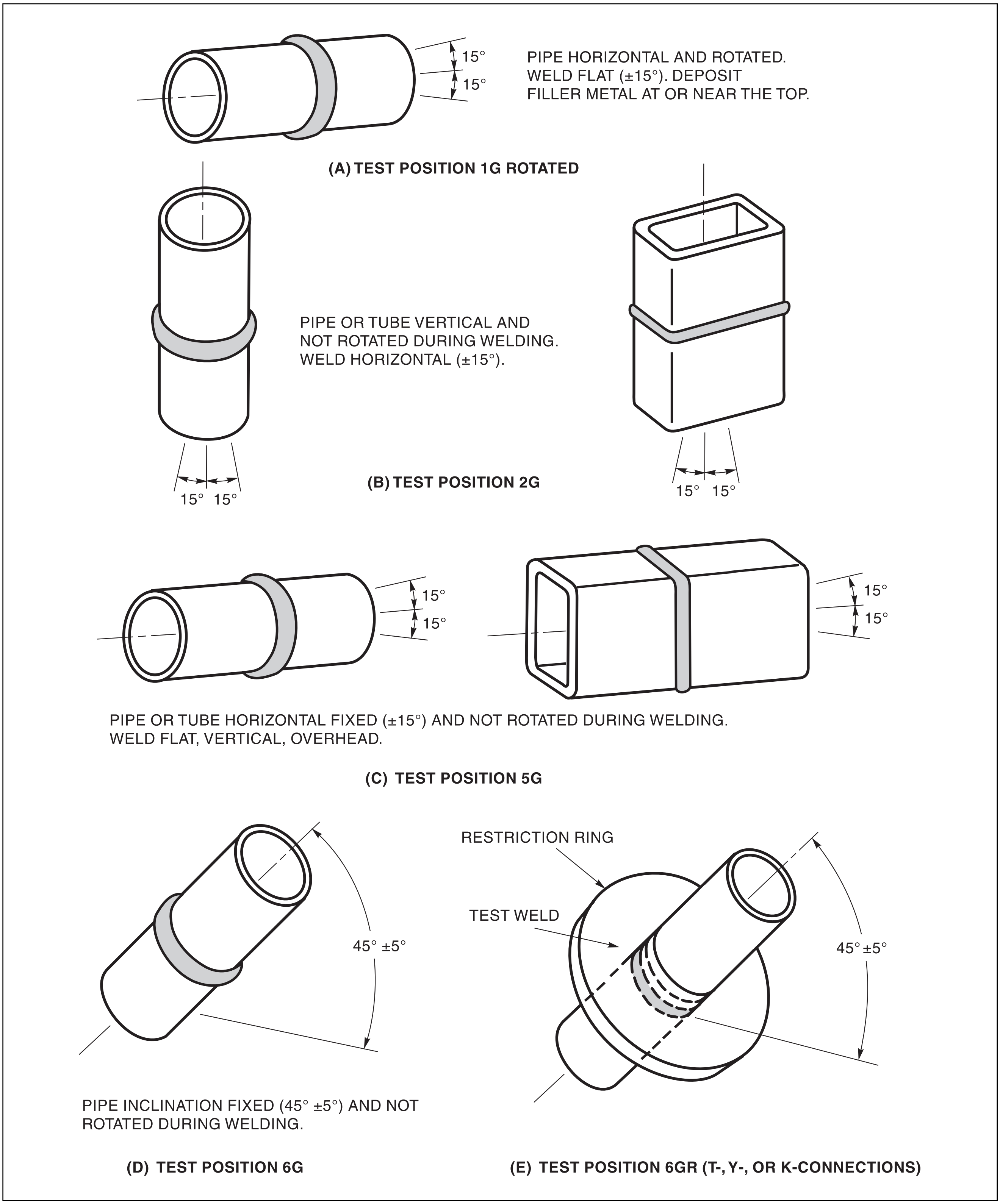
Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 4.3.

Figure 15.1—Positions of Test Plates for Groove Welds

Peening. Peening is used to minimize the amount of shrinkage of the weld metal during cooling. It is also used to avoid the cracking or distortion of the weld or base metals. The details of its application and the appropriate tooling required should be specified in the welding procedure specification. The casual or indiscriminate use of peening should not be permitted without the approval of the welding engineer or quality control personnel. Peening of the finished weld is generally not recommended.

Heat Input. Heat input during welding is usually of great importance when welding heat-treated steels and crack-sensitive ferrous and nonferrous alloys. Whenever heat input can influence final properties of the weld joint, details for its control should be prescribed in the welding procedure specification.

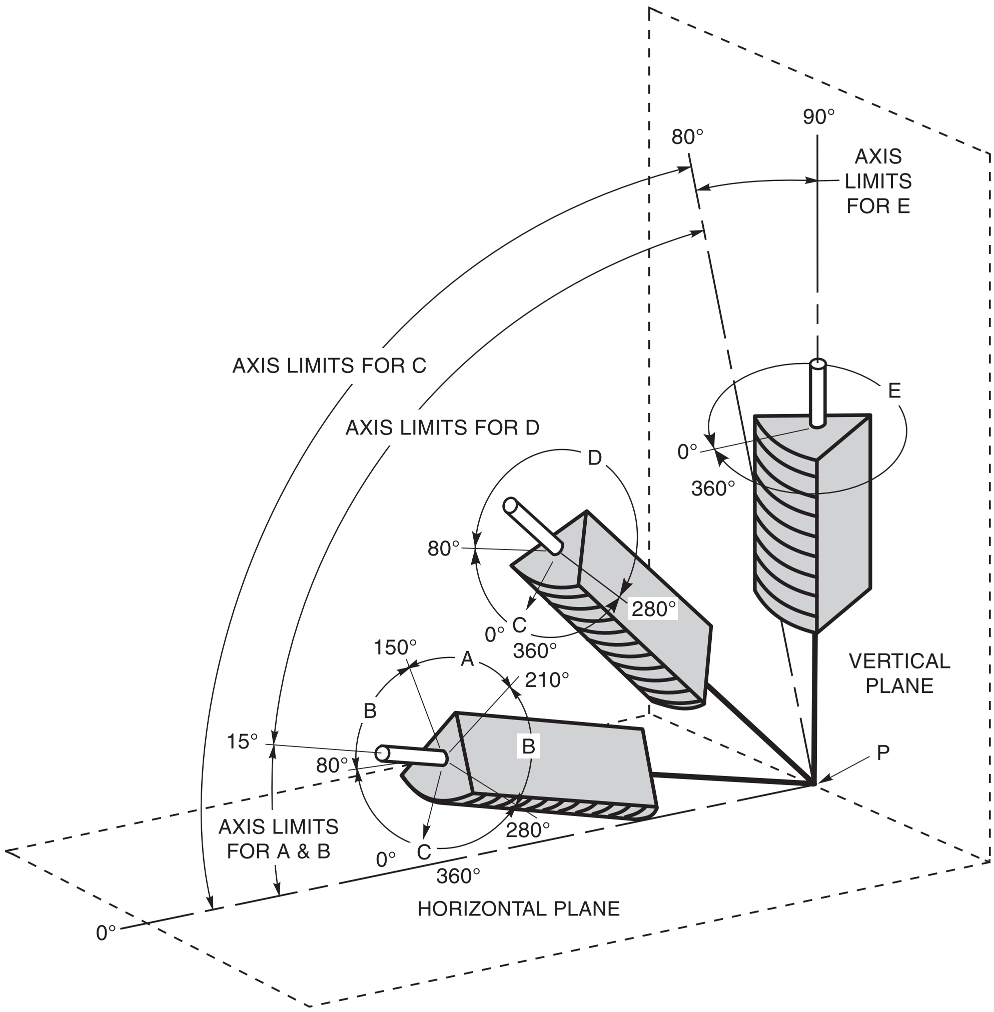
Second Side Preparation. When joints are to be welded from both sides, the methods that are to be used to prepare the second side should be described in the welding procedure specification. These may include chipping; grinding; and air-carbon arc, plasma, or oxyfuel gas gouging of the root pass to sound metal. If the second side requires an inspection other than visual, this should also be prescribed. This preparation is frequently of primary importance in the production of weld joints that are fully penetrated and free from cracks and other imperfections.



Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 4.4.

Figure 15.2—Positions of Test Pipe or Tubing for Groove 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 E	15° to 80° 80° to 90°	80° to 280° 0° to 360°



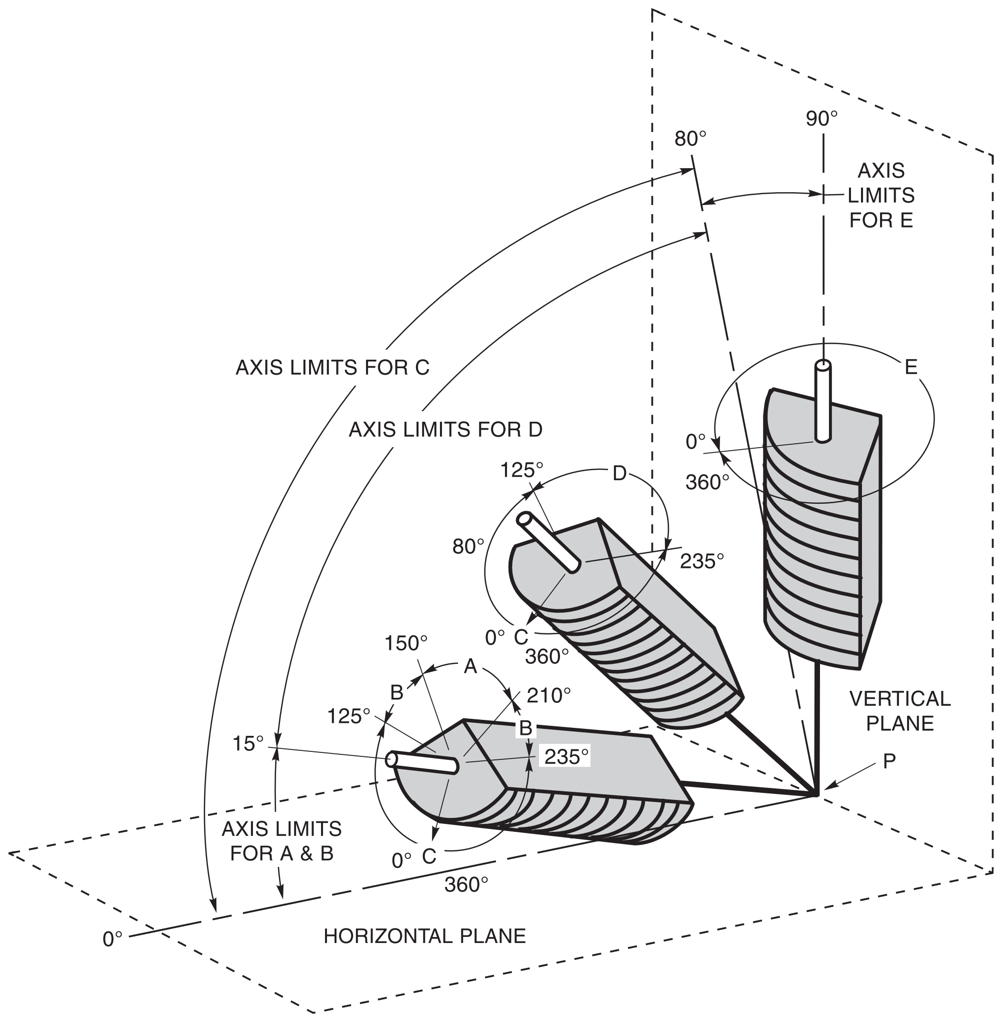
Notes:
1. Variables A, B, C, D, E, and P represent geometric planes or points used to describe the relative position of the weld area during qualification.
2. The horizontal reference plane is always taken to lie below the weld under consideration.
3. The inclination of axis is measured from the horizontal reference plane toward the vertical reference plane.
4. 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°).

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 4.1.

Figure 15.3—Positions of Groove Welds

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 E	15° to 80° 80° to 90°	125° to 235° 0° to 360°



Note: Variables A, B, C, D, E, and P represent geometric planes or points used to describe the relative position of the weld area during qualification.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Figure 4.2.

Figure 15.4—Positions of Fillet Welds

Postweld Heat Treatment. When welded joints or structures require heat treatment after welding to develop the desired mechanical properties and dimensional stability or to reduce residual stresses, such treatment should be described in the welding procedure specification. Any heat treatment that is applied to production welds is required to be similarly applied to all procedure qualification test coupons. A full description of the heat treatment may appear in the welding procedure specification or in a separate fabrication document such as a shop heat treating procedure. Heat treatment requirements can be obtained in the appropriate construction or fabrication code.

Records

The methods used to record the manufacturer's weld procedures, welders' qualifications, and the results of the inspection of welded joints are typically established in quality control documentation. Each manufacturer should have such a quality control manual or program to establish, as a minimum, the requirements that are to be recorded per the requirements of the clients and the applicable codes.

Welding Procedure Specification Forms

A welding procedure specification may be brief and concise or long and detailed. The codes dictate the minimum required information, usually referred to as *essential* and *nonessential variables*. Some codes include recommended forms. These forms are typically optional and may not contain spaces for all the required information for some processes. When complex and critical welding is anticipated, welding procedure specifications should provide the welder more details than the minimum required. Such details to suit the situation may be provided directly in the WPS through revision, by additional notes attached to the WPS, by instructions in separate procedures, or directly on construction drawings.

The American Welding Society (AWS) and the Welding Research Council (WRC) have collaborated to create standard procedures for the welding industry. These standards are for specific welding processes and groups of base metals with certain thicknesses. An example of such a standard is *Standard Welding Procedure (WPS) for Shielded Metal Arc Welding of Carbon Steel, (M-1/P-1/S-1, Group 1 or 2), 1/8 through 1-1/2 Inch Thick, E7018, As-Welded or PWHT Condition*, ANSI/AWS B2.1-1-016.[38]

A sample welding procedure specification form is presented in Figures 15.5(A) and (B). This form, as noted in its titles, can be used for new weld procedures and for those procedures that may be prequalified. A procedure identified as "prequalified" on the first page of this form [Figure 15.5(A)] would not require the use of the second page [Figure 15.5(B)]. Further discussions of prequalified procedures are presented later in this chapter.

WELDING PROCEDURE SPECIFICATIONS FOR OXYFUEL GAS WELDING

The principles involved in the preparation of a welding procedure specification for oxyfuel gas welding are the similar to those used for arc welding. However, because of the difference in the welding processes, additional qualification variables exist for oxyfuel welding. Some standards, such as *Welding and Brazing Qualifications*, Section IX of the *1998 ASME Boiler and Pressure Vessel Code*, include a detailed chart (in this case, Table QW-252) for the essential and nonessential variables that relate to oxyfuel gas welding.[39]

Content

Typical variables that need to be included in a welding procedure specification prepared for oxyfuel gas welding are joint design, base metal, filler metal, postweld heat treatment, and technique. Due to the nature of this process, the type of fuel gas is also an essential variable. In addition, for some applications of oxyfuel welding, other variables such as tip size must be included.

Fuel Gas. The type of fuel gas used is a qualification variable that must be specified. All fuel gases have different characteristics that affect the flame temperature and thus the weld speed or the thickness of the workpiece that can be welded. Even though oxygen is always used to support combustion, it should be mentioned in the procedure. The flame type—whether oxidizing, reducing, or neutral—should also be included in the welding procedure specification.

Tip Size. The torch tip permits the welder to direct the flame toward the workpiece. As torch tips are available in a wide variety of sizes and shapes, selection can make the job easier or more difficult. Manufacturers' information should be used in determining the proper tip size and shape to be used for the workpiece. Tip size or sizes to be used in the welding operation for hardfacing

38. American Welding Society (AWS) Committee on Welding Qualification, *Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Carbon Steel, (M-1/P-1/S-1, Group 1 or 2), 1/8 through 1-1/2 Inch Thick, E7018, As-Welded or PWHT Condition*, ANSI/AWS B2.1-1-016, Miami: American Welding Society.

39. See Reference 35.

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☐
PREQUALIFIED __________ QUALIFIED BY TESTING __________
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐

Identification # ____________________
Revision ______ Date __________ By __________
Authorized by ____________________ Date __________
Type—Manual ☐ Semi-Automatic ☐
Machine ☐ Automatic ☐

Company Name ____________________
Welding Process(es) ____________________
Supporting PQR No.(s) ____________________

JOINT DESIGN USED
Type:
Single ☐ Double Weld ☐
Backing: Yes ☐ No ☐
Backing Material:
Root Opening ______ Root Face Dimension ______
Groove Angle: ______ Radius (J–U) ______
Back Gouging: Yes ☐ No ☐ Method ______

BASE METALS
Material Spec. ____________________
Type or Grade ____________________
Thickness: Groove __________ Fillet __________
Diameter (Pipe) ____________________

FILLER METALS
AWS Specification ____________________
AWS Classification ____________________

SHIELDING
Flux __________ Gas __________
Composition __________
Electrode-Flux (Class) ______ Flow Rate __________
__________ Gas Cup Size __________

PREHEAT
Preheat Temp., Min ____________________
Interpass Temp., Min ______ Max ______

POSITION
Position of Groove: __________ Fillet: __________
Vertical Progression: Up ☐ Down ☐

ELECTRICAL CHARACTERISTICS
Transfer Mode (GMAW) Short-Circuiting ☐
Globular ☐ Spray ☐
Current: AC ☐ DCEP ☐ DCEN ☐ Pulsed ☐
Other ____________________
Tungsten Electrode (GTAW)
Size: __________
Type: __________

TECHNIQUE
Stringer or Weave Bead: ____________________
Multi-pass or Single Pass (per side) ____________________
Number of Electrodes ____________________
Electrode Spacing Longitudinal __________
Lateral __________
Angle __________
Contact Tube to Work Distance ____________________
Peening ____________________
Interpass Cleaning: ____________________

POSTWELD HEAT TREATMENT
Temp. ____________________
Time ____________________

SAMPLE

WELDING PROCEDURE

Pass or Weld Layer(s)	Process	Filler Metals		Current		Volts	Travel Speed	Joint Details
		Class	Diam.	Type & Polarity	Amps or Wire Feed Speed			

Form E-1 (Front)

Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Annex E, Form E-1, p. 300.

Figure 15.5(A)—Suggested Format for Welding Procedure Specification (WPS) (Front)

Procedure Qualification Record (PQR) # __________
Test Results

TENSILE TEST

Specimen No.	Width	Thickness	Area	Ultimate Tensile Load, lb	Ultimate Unit Stress, psi	Character of Failure and Location

GUIDED BEND TEST

Specimen No.	Type of Bend	Result	Remarks

VISUAL INSPECTION
Appearance ______________________
Undercut ______________________
Piping porosity ______________________
Convexity ______________________
Test date ______________________
Witnessed by ______________________

Radiographic-ultrasonic examination
RT report no.: __________ Result __________
UT report no.: __________ Result __________

FILLET WELD TEST RESULTS
Minimum size multiple pass Maximum size single pass
Macroetch Macroetch
1. ________ 3. ________ 1. ________ 3. ________
2. ________ 2. ________

Other Tests

All-weld-metal tension test

Tensile strength, psi ______________________
Yield point/strength, psi ______________________
Elongation in 2 in., % ______________________
Laboratory test no. ______________________

Welder's name ______________________ Clock no. __________ Stamp no. __________

Tests conducted by ______________________ Laboratory

Test number ______________________

Per ______________________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of AWS D1.1, (__________) Structural Welding Code—Steel.
(year)

Signed ______________________
Manufacturer or Contractor

By ______________________

Title ______________________

Date ______________________

Form E-1 (Back)

Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Annex E, Form E-1, p. 304.

Figure 15.5(B)—Suggested Format for Welding Procedure Specification (WPS) (Back)

overlay must also be specified. These are based on the orifice size, and they control the amount of gas consumption as well as weld cost.

Fuel and Oxygen Pressures. The pressure ranges of the oxygen and fuel gas for welding should be specified in any supplementary notes that may accompany an oxyfuel welding procedure specification. These are not listed as essential variables, but pressures vary depending on the fuel gas and welding equipment used.

Joint Design and Tolerances. It is important to define the limitations that may be encountered by the welder in completing an acceptable weld. The joint design must be included on the welding procedure specification. This may be accomplished by adding words, sketches, or references to construction drawings.

Joint and Surface Preparation. The welding procedure specification should indicate the methods of joint preparation and cleaning that are to be used. Although these are nonessential variables (which may make them seem unimportant), they require the employer to provide the welder specific directions for the production of an acceptable weld.

Tack Welding. Details relating to the tack welds required for the assembly should be specified in the supplementary notes pertaining to the welding procedure. These include the number, size, and frequency or location of these tack welds.

Welding Details. All welding details, essential and nonessential, that affect weld quality should be provided in the welding procedure specification. The number of passes or layers required, the size of the filler metal used, the rate or speed of travel, and the width of the weave should be recorded. Any pertinent facts that help define the welding process should be included in the supplementary notes that accompany the welding procedure specification.

Welding Positions. Although oxyfuel gas welding may be performed in any position, it may be advantageous to use certain positions only. The welding procedure specification should state the positions for which the process was intended. When establishing a procedure, consideration should be given not only to all possible positions but also to those that are the most practical.

WELDING PROCEDURE SPECIFICATIONS FOR RESISTANCE WELDING

The principles involved in the preparation of a welding procedure specification for resistance welding are similar to those used for arc welding. However, because of the nature of the process, additional qualification variables exist as well. Some standards, such as *Welding and Brazing Qualifications*, include a detailed chart (in this case, Table QW-263) for the essential and nonessential variables involved in resistance welding.[40]

Content

The items that are typically detailed in a welding procedure specification for resistance welding are discussed below. Others may be required, depending on the particular resistance welding process used.

Welding Process. The various resistance welding processes are distinct in many respects; therefore, the welding procedure specification should indicate the specific resistance welding process to be used (e.g., spot, seam, or projection welding) for the job.

Composition and Condition of the Base Metal. Information regarding the composition and condition of the base metal is of great importance. A welding procedure that produces excellent results with one base metal may not be satisfactory for use with another base metal or for a different heat treatment or cleanliness condition.

The base metal to be welded should be specified either by reference to a specification or by chemical composition. The permissible chemical composition range may include base metals covered by more than one specification if they can be welded using the same procedure. The condition (temper) of the base metal should be clearly stated. The welding procedure specification should also prescribe any specific cleaning requirements.

Joint Design. The welding procedure specification should specify all details of the joint design. These include overlap, weld spacing, the type and size of projection, and other characteristics.

Type and Size of Electrode. The welding procedure specification should indicate the type of electrode to be used. The alloy, contour, and size should be specified. If plates, dies, blocks, or other such devices are used, any properties that might affect the quality of welding should also be included.

Machine Settings. The electrode force, squeeze time, weld time, hold time, off-time, welding speed, upset time, and other variables that are controlled by machine settings should be specifically prescribed in the welding procedure specification.

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40. See Reference 35.

Weld Size and Strength. As the size or strength of the weld is generally an acceptance criterion, information regarding size and strength should be included in the welding procedure specification.

Surface Appearance. Factors that may affect the surface appearance of a weldment should be specified. These include indentation, discoloration, and amount of upset, among others. These factors may be governed by a general requirement rather than various requirements, however.

Inspection Details. The weld properties that are subject to inspection should be specified in the welding procedure specification. These include appearance, strength, and tightness. The testing methods to be used should also be indicated. These may include the shear test, the pillow test, the peel test, or a workmanship sample, for example.

BRAZING PROCEDURE SPECIFICATIONS

Brazing procedure specifications (BPS) and procedure qualification records (BPQR) are similar to those used for arc welding except for the process data. Process information may include but is not be restricted to the following:

1. Type of brazing (torch, furnace, induction, resistance, dip, or infrared);
2. Brazing filler metal and form;
3. Brazing temperature range;
4. Brazing flux or atmosphere;
5. Flow position;
6. Method of applying filler material;
7. Time at brazing temperature; and
8. Heating and cooling rates.

Sample Brazing Procedure Specification Form

A sample brazing procedure specification (BPS) form is presented in Figure 15.6.

Typical brazing flow positions are flat, vertical down, vertical up, and horizontal. In flat flow, the joint faces and capillary flow are horizontal. In vertical-down flow and vertical-up flow, the joint faces are vertical, and the capillary flow of filler metal travels down and up, respectively. With horizontal flow, the joint faces are also vertical, but the capillary flow of the filler metal is horizontal.

Typical codes and standards that address brazing qualifications are *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2,[41] and the *Welding and Brazing Qualifications*, Section IX of the *Boiler and Pressure Vessel Code*.[42]

QUALIFICATION OF WELDING AND BRAZING PROCEDURES

In the writing of a welding or brazing procedure specification, the engineer establishes a set of parameters that can continue to be used in future designs. After a weld procedure specification is written, it needs to be tested to verify that the results meet the overall expectations or design criteria. Procedure qualification tests are conducted in accordance with a specific code or standard as the basis of design. Upon completion of testing, if the results are acceptable, they are recorded on a procedure qualification record (PQR). The procedure qualification record is then signed by the responsible member of the organization and becomes available for use in production.

The purpose of procedure qualification is to ensure, by means of the preparation and testing of specimens, that welding performed in accordance with the welding procedure specification will produce sound welds and adequate joint properties. The type and number of tests required are designated in Section QW-202 of the *Welding and Brazing Qualifications*,[43] Section IX of the *1998 Boiler and Pressure Vessel Code* and in *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1.[44] The tests are selected to provide sufficient information about the strength, ductility, toughness, and other properties of the joint. The qualification variables are specified to maintain the desired properties. When significant changes are made to WPS qualification variables, the properties of the weld joint may be affected, and requalification is required.

The mechanical and metallurgical properties of a welded joint may be altered by the welding procedure specification selected for the job. It is the employer's responsibility to conduct the qualification tests required by the applicable codes and contractual documents. It is the duty of the engineer or inspector to review and evaluate the results of these qualification tests.

Qualification activities must be completed prior to production to assure that the selected combination of methods and materials is capable of achieving the desired results. The rules for the qualification of welding

41. See Reference 26.
42. See Reference 21.
43. See Reference 35.
44. See Reference 25.

Form A1

BRAZING PROCEDURE SPECIFICATION (BPS)

BPS No. ____________ Date ______________ B PQR NO. __________

Company ____

Brazing Process ____________________ Manual ☐ Mechanized ☐ Automatic ☐

Brazing Equipment ____

BRAZING CONDITIONS

BASE METAL:

Identification ____________________________ BM No. __________

Thickness ____________ Preparation ____________________________

Other ____

FILLER METAL:

FM No. __________ AWS Classification ____________________________

Form ____________________ Method of Application ______________

FLUX: AWS Type ______________ [illegible] ____________________

ATMOSPHERE: AWS Type ______________

TEMPERATURE: ______________ TEST POSITION: ______________

TIME: ______________ CURRENT: ______________

FUEL GAS: ______________ TIP SIZE: ______________

POSTBRAZE CLEANING: ____________________________________

POSTBRAZE HEAT TREATMENT: ____________________________________

OTHER: ____

JOINT:

Type ____________________

Clearance ____________________

UTS ____________________

Other ____________________

____

Approved for production by ____________________ JOINT SKETCH

Employer

Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Appendix A, Form A1.

Figure 15.6—Sample Brazing Procedure Specification (BPS) Form

procedures are typically established by the fabrication standard.

QUALIFICATION TESTS

The purpose of procedure qualification testing is to determine that the weldment proposed for construction has the required properties for its intended application. Qualification testing does not always simulate the actual conditions encountered during production welding. It is the responsibility of the manufacturer or contractor to provide appropriate direction to the welder by means of the welding procedure specifications to ensure that the weldments he or she makes are suitable for the intended application.

Procedure qualification testing usually requires making a butt groove weld on pipe or plate. Fillet weld testing is also sometimes required or may be permitted as an alternate to groove welding. The welding process, base metals, filler metals, and preheat and postweld heat treatments that are to be used to weld the test coupon must be established based on the welding process, base metals, filler metals, and preheat and postweld heat treatments that will be used in production welding. In some cases, the welder who welds the test coupon is provided a preliminary welding procedure specification to follow; however, this is not a typical code requirement.

Mock-up tests simulate actual production conditions to the extent necessary to determine that a sound plan that implements certain tooling and inspection activities has been selected. Welding codes do not generally require the preparation of mockups or joint samples unless these are needed to demonstrate that the welding procedures have the capacity to produce the specified welds. Nonetheless, the preparation of mockups or sample joints may be required to satisfy contractual conditions or to avoid production problems. With respect to production, mockups can indicate the quality levels that can expected under difficult or restricted welding conditions.

PREQUALIFIED JOINT WELDING PROCEDURES

The concept of a prequalified joint welding procedure is based on the reliability of certain proven procedures that have been established by an applicable code or specification. *Structural Welding Code—Steel*, AWS D1.1[45] is one such code that utilizes prequalified joint procedures. The use of such a prequalified procedure exempts a manufacturer from having to test the procedure and verify its results. It does not relieve the welding engineer from using sound judgement in the application for the project, however. The prequalified procedure, which takes the form of a written document, gives direction to all welders utilizing the process. Any deviation from the specified parameters results in the voiding of the prequalification.

45. See Reference 6.

WELDING PROCEDURES

The basic steps involved in the qualification of welding procedures are presented below:

1. The grade of base metals to be joined, the desired results, the joining processes to be used, the appropriate construction or fabrication code, and the acceptance criteria are determined;
2. A preliminary welding procedure specification is drafted;
3. An appropriate test coupon is welded following a preliminary welding procedure specification;
4. Required destructive and nondestructive examinations are conducted;
5. Results of the examination and the test specimens are evaluated;
6. The welding conditions (variables) present during the welding of the test coupon and the test results are documented in a procedure qualification record;
7. The welding procedure specification (see Figure 15.5) is finalized; and
8. The welding procedure specification and the performance qualification record are approved by the employer as required by the organization's operating procedures or quality assurance/quality control system (QA/QC), as appropriate.

Codes may or may not furnish documentation forms for record-keeping purposes. Some codes include suggested forms whose use is not mandatory. The information provided on these forms typically meets only the minimum requirements. It is common practice and perfectly acceptable with respect to codes for a manufacturer to prepare its own forms or to use text format, provided the welding procedure specification has all the information that is required to be recorded by the applicable code (usually the essential variables).

Preparation of Sample Joints

Test coupons for qualification are made from plate or pipe, and the joint design used is typical of one used in production welding. The base and filler metals and other details associated with the welding of sample joints are selected in accordance with the particular procedure specification that is being qualified. The size, type, and thickness of the samples is determined by the thickness and type of base metal to be welded in production and by the type, size, and number of specimens to be removed for testing. The latter are prescribed by the applicable code or specification. Examination of the test coupon weld by means of the nondestructive methods is common practice and may be required by some codes.

Testing of Procedure Qualification Welds

Test specimens are removed from predetermined locations in the test coupon to determine the properties of the weldment. The type, number, and size of the specimens to be removed and the details of the testing are dictated by the code or specification being followed. Testing typically involves tensile and guided bend specimens to determine strength, ductility, soundness, and adequacy of fusion. The grade of material and the thickness of the specimens determine the size and radius of the bender to be used. If fillet welds alone are tested, tension-shear test and break- or macroetch-test specimens are removed.

Additional testing techniques may be specified by the applicable codes or contract documents to meet specific needs. These techniques may include the following:[46]

1. Impact tests, which are used to determine the notch toughness of the weld and the heat-affected zone. These are conducted at the specified system operating temperature to indicate the likelihood of brittle fracture at that temperature. The Charpy V-notch test is commonly employed, but other tests, including the drop-weight and crack-opening-displacement (COD) tests, are sometimes used;
2. Nick-break tests, which are used to assess weld soundness at randomly selected locations;
3. Free-bend tests, which are used to evaluate the ductility of weld metal;
4. Shear tests, which are performed to determine the shear strength of fillet welds or clad bonding;
5. Hardness tests, which are conducted to evaluate the adequacy of heat treatment and the suitability of the weld for particular service conditions. These tests may be performed on surfaces or cross sections of welds;
6. All-weld-metal tension tests, which are used to appraise the mechanical properties of the weld metal in a diluted condition;
7. Elevated-temperature tests, which are employed to determine the mechanical properties at service temperatures;
8. Restraint tests, which are conducted to evaluate crack susceptibility and the ability to achieve sound welds under restrained conditions;
9. Corrosion tests, which are used to determine the properties needed to withstand aggressive environments;
10. Macroetch or microetch tests, which are used to examine the soundness of a weld; and
11. Delayed cracking tests, which are applied to detect resistance to hydrogen cracking in high-strength, low-alloy steels, and some other alloys; and
12. Nondestructive tests, which are used to determine the presence of features or defects that could prove injurious to the weld in service.

Recording of Test Results

Test details and the results of all tests and examinations are entered on a procedure qualification record, as shown in Figure 15.7. When the qualifier is satisfied that the records and the results are accurate, he or she signs the performance qualification record, thereby certifying the results. When the results meet the requirements of a job specification, the welding procedure specification can then be prepared and issued for production welding. Since the performance qualification record is certified, it should not be revised. If information needs to be added later, additions are usually made in the form of a supplement or attachment, as records should not be changed by revision. A single performance qualification record may support several welding procedure specifications. Likewise, several performance qualification records may support one welding procedure specification.

In evaluating a welding procedure or the test results, applicable codes provide general guidance and some specific acceptance and rejection criteria. For instance, the minimum tensile strength and the maximum number of inclusions or other discontinuities that may be present are specified by many codes. The acceptability of other properties should be based on sound engineering judgment.

Although it is desirable that the weld match the mechanical and metallurgical properties of the base metal, this is not always possible. Not only are the weld metal and the base metal made of different product forms, but they also often have somewhat different chemical compositions and mechanical properties. Good engineering judgment is required in the selection of the most important properties for each application. This is especially important for service at high or low temperatures, highly corrosive conditions, and severe fatigue applications.

46. Standard welding tests are discussed in detail in American Welding Society (AWS) Committee on Mechanical Testing of Welds, *Standard Methods for Mechanical Testing of Welds,* ANSI/AWS B4.0 and AWS B4.0M, Miami: American Welding Society.

Procedure Qualification Record (PQR) # __________
Test Results

TENSILE TEST

Specimen No.	Width	Thickness	Area	Ultimate Tensile Load, lb	Ultimate Unit Stress, psi	Character of Failure and Location

GUIDED BEND TEST

Specimen No.	Type of Bend	Result	Remarks

VISUAL INSPECTION
Appearance ______________________
Undercut ______________________
Piping porosity ______________________
Convexity ______________________
Test date ______________________
Witnessed by ______________________

Radiographic-ultrasonic examination
RT report no. __________ Result __________
UT report no. __________ Result __________

FILLET WELD TEST RESULTS
Minimum size multiple pass Maximum size single pass
Macroetch Macroetch
1. ________ 3. ________ 1. ________ 3. ________
2. ________ 2. ________

Other Tests

All-weld-metal tension test

Tensile strength, psi ______________________
Yield point/strength, psi ______________________
Elongation in 2 in., % ______________________
Laboratory test no. ______________________

Welder's name ______________________ Clock no. __________ Stamp no. __________

Tests conducted by ______________________ Laboratory

Test number ______________________

Per ______________________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of AWS D1.1, (__________) Structural Welding Code—Steel.
(year)

Signed ______________________
Manufacturer or Contractor

By ______________________

Title ______________________

Date ______________________

Form E-1 (Back)

Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, Annex E, Form E-1, p. 304.

Figure 15.7—Suggested Format for Procedure Qualification Record (PQR) (Back)

Changes in a Qualified Procedure

If a fabricator desires to make a major change to an existing welding procedure specification (e.g., a revision to an essential variable), it is usually necessary to conduct additional procedure qualification tests. These additional tests establish that the new version of the welding procedure specification will produce satisfactory welds.

Additional qualification tests are not usually required when minor details (e.g., nonessential variables, editorial changes, or instructions to the welder that are not addressed by a code) are changed. These tests must establish that the changed welding procedure produces satisfactory results.

The governing code or specification should always be consulted to determine whether an essential variable has been changed. Typical procedure factors that may require requalification of the welding procedure specification are the process-specific essential variables presented in Table 15.1.

Resistance Welding Procedures

A proposed welding procedure must be evaluated by means of the appropriate testing methods to determine whether the joints produced using the procedure can be welded consistently and satisfactorily meet the service requirements to which they will be exposed. Because of the diverse nature of resistance welded products, the qualification of resistance welding procedures is also varied.

As a rule, when the weldment is small in size, the procedure may be qualified by making a number of finished pieces and testing them to destruction under simulated or real service conditions. In other instances, welds can be made in specimens that are tested in tension or shear or inspected for other properties.[47]

Three main steps are followed in the qualification of a resistance welding procedure. These steps—the preparation of weld specimens, the testing of the specimens, and the evaluation of test results—are discussed below.

Preparation of Weld Specimens. Sample weld specimens are prepared and welded in accordance with the welding procedure specification to be qualified. The number, size, and type of samples are determined by the nature of the tests to be performed for qualification. When qualification is performed in accordance with a standard, these requirements are usually specified.

Testing of Specimens. The nature of the tests performed varies according to the service requirements of the completed weldments. Test specimens may be subjected to real or simulated service conditions. More frequently, however, tests are performed to determine specific properties of the weld. These include tensile strength, shear strength, surface appearance, and soundness.

Evaluation of Test Results. Once the welded specimens have been tested, the results are reviewed to determine whether they meet the specified requirements. If all the requirements are met, the welding procedure is considered qualified.

BRAZING PROCEDURES

Brazing procedure specifications are qualified by brazing test coupons and testing them using test specimens and acceptance criteria that are appropriate for brazed joints. Typical tests and applicable joints are presented in Table 15.4 and Figure 15.15 (see below). The results of these tests are recorded on the brazing procedure qualification record (PQR), shown in Figures 15.8(A) and (B). This record lists the information included on the brazing procedure specification as well as the results of the appropriate tests. The record is then certified by the employer's representative, who witnessed the tests.

The *Standard for Brazing Procedure and Performance Qualification,* ANSI/AWS B2.2,[48] and Section QB of the ASME *Welding and Brazing Qualifications*[49] describe the types and conditions for brazing qualification in further detail.

Table 15.4
Brazing Procedure Qualification Tests

Test	Applicable Joints	Properties Evaluated
Tension	Butt, scarf, lap, rabbet	Ultimate strength (tension or shear)
Guided bend	Butt, scarf	Soundness, ductility
Peel	Lap	Bond quality, soundness

47. Standard tests for resistance welds are provided in American Welding Society (AWS) Committee on Resistance Welding, *Recommended Practices for Resistance Welding,* AWS C1.1M/C1.1, Miami: American Welding Society. Resistance welded butt joints can be evaluated using mechanical tests that are similar to those used for arc welded joints.

48. See Reference 26.
49. See Reference 35.

Form A2 **Sheet 1 of 2**

PROCEDURE QUALIFICATION RECORD (PQR)

BPQR No. ____________ Date ____________ BPS NO. ____________

Company ______________________________

Brazers' Name and Id. ______________________________

Brazing Process ____________________ Manual ☐ Mechanized ☐ Automatic ☐

Brazing Equipment ______________________________

BRAZING CONDITIONS

BASE METAL:

Identification ____________________ BM No. ____________

Thickness ____________ Preparation ____________

Other ______________________________

FILLER METAL:

FM No. ____________ AWS Classification ____________

Form ____________ Method of Application ____________

FLUX: AWS Type ____________ Other ____________

ATMOSPHERE: AWS Type ____________

TEMPERATURE: ____________ TEST POSITION: ____________

TIME: ____________ CURRENT: ____________

FUEL GAS: ____________ TIP SIZE: ____________

POSTBRAZE CLEANING: ______________________________

POSTBRAZE HEAT TREATMENT: ______________________________

OTHER: ______________________________

JOINT:

Type ____________

Clearance ____________

Other ____________

____

JOINT SKETCH

Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Appendix A, Form A2.

Figure 15.8(A)—Sample Brazing Procedure Qualification Record (PQR) Form (Front)

Form A2 Sheet 2 of 2

TEST RESULTS

BPQR No. ____________________ Date ____________

VISUAL

	Pass	Fail

TENSION

Specimen No.	UTS psi	Remarks	Pass	Fail

BEND

Specimen No.	Remarks	Pass	Fail

MACROETCH

Specimen No.	Remarks	Pass	Fail

PEEL

Specimen No.	Remarks	Pass	Fail

We certify that the information in this record is correct and that the test brazements were prepared, brazed, and tested in accordance with the requirements of the American Welding Society *Standard for Brazing Procedure and Performance Qualification,* ANSI/AWS B2.2-91.

Approved by ______________________
Qualifier

Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Appendix A, Form A2.

Figure 15.8(B)—Sample Brazing Procedure Qualification Record (PQR) Form (Back)

Base Metals

The groupings of base metals used in brazing are similar to those utilized in welding. The American Welding Society's groupings of brazing materials are listed in *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Appendix B, Table B1.[50] ASME's base metal groupings are presented in Table QW/QB-422 in *Welding and Brazing Qualifications*, Section IX of the *Boiler and Pressure Vessel Code*.[51]

Brazing Positions

Like welding procedures, brazing procedures are developed and tested for one or more positions encountered in production brazing. Procedures should be developed for the anticipated joint configuration and direction of the flow of the filler metal to ensure joints of consistent quality. Brazers should be tested and qualified to those procedures to ensure they can produce production brazed joints of consistent quality.

The position of the brazed joint is important in both torch brazing and furnace brazing. Careful attention must be paid to this variable. Brazing positions for procedure or performance qualification are shown in Figure 15.9.

50. American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society.
51. See Reference 21.

Filler Metals

Brazing filler metals are classified similar to those used for welding. A listing of brazing filler metals is presented in Appendix C of *Specification for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91.[52] Brazing filler metals are given a filler metal (FM) number, as listed in Table 15.5.

52. See Reference 50.

Table 15.5
Filler Metal (FM) Groups

FM-No.	AWS Classification	UNS No.	Approximate Chemical Composition, Weight Percent (wt %)										Solidus °F (°C)	Liquidus °F (°C)	Brazing Temperature °F (°C)
			Ag	Cu	Zn	Cd	Ni	Sn	Li	Mn	Pd	In			
100	BAg-1	P07450	45	15	16	24	—	—	—	—	—	—	1125 (608)	1145 (618)	1145–1400 (618– 760)
	BAg-1A	P07500	50	15	16	18	—	—	—	—	—	—	1160 (627)	1175 (635)	1175–1400 (635–760)
	BAg-8	P07720	72	Rem.*	—	—	—	—	—	—	—	—	1435 (779)	1435 (779)	1435–1650 (779–899)
	BAg-8a	P07723	72	Rem.	—	—	—	—	0.4	—	—	—	1410 (766)	1410 (766)	1410–1600 (766–871)
	BAg-22	P07490	49	16	23	—	4.5	—	—	7.5	—	—	1260 (680)	1290 (699)	1290–1525 (699–830)
	BAg-23	P07850	85	—	—	—	—	—	—	Rem.	—	—	1760 (960)	1780 (970)	1780–1900 (970–1038)
	BVAg-0	P07017	100	—	—	—	—	—	—	—	—	—	1761 (961)	1761 (961)	1761–1900 (961–1038)
	BVAg-8	P07727	72	Rem.	—	—	—	—	—	—	—	—	1435 (779)	1435 (779)	1435–1650 (779–899)
	BVAg-8b	P07728	72	Rem.	—	—	0.5	—	—	—	—	—	1435 (779)	1463 (795)	1470–1650 (799–899)
	BVAg-30	P07687	68	Rem.	—	—	0.5	—	—	—	5	—	1485 (807)	1490 (810)	1490–1700 (810–927)
110	BAg-2	P07350	35	26	21	18	—	—	—	—	—	—	1125 (607)	1295 (702)	1295–1500 (702–843)

*Rem. = Remainder

(Continued)

Table 15.5 (Continued)
Filler Metal (FM) Groups

FM-No.	AWS Classification	UNS No.	Approximate Chemical Composition, Weight Percent (wt %)										Solidus °F (°C)	Liquidus °F (°C)	Brazing Temperature °F (°C)
			Ag	Cu	Zn	Cd	Ni	Sn	Li	Mn	Pd	In			
110 (Cont'd)	BAg-2a	P07300	30	27	23	20	—	—	—	—	—	—	1125 (607)	1310 (710)	1310–1550 (710–843)
	BAg-3	P07501	50	15	15	16	3.0	—	—	—	—	—	1170 (632)	1270 (688)	1270–1500 (688–816)
	BAg-4	P07400	40	30	28	—	2.0	—	—	—	—	—	1240 (671)	1435 (779)	1435–1650 (779–899)
	BAg-5	P07453	45	30	25	—	—	—	—	—	—	—	1225 (663)	1370 (743)	1370–1550 (743–843)
	BAg-6	P07503	50	34	16	—	—	—	—	—	—	—	1270 (688)	1425 (774)	1425–1600 (774–871)
	BAg-7	P07563	56	22	17	—	—	5	—	—	—	—	1145 (618)	1205 (652)	1205–1400 (652–760)
	BAg-9	P07650	65	20	15	—	—	—	—	—	—	—	1240 (672)	1325 (718)	1325–1550 (718–843)
	BAg-10	P07700	70	20	10	—	—	—	—	—	—	—	1275 (691)	1360 (738)	1360–1550 (718–843)
	BAg-13	P07540	54	Rem.	5	—	1.0	—	—	—	—	—	1325 (718)	1575 (858)	1575–1775 (858–969)
	BAg-13a	P07560	56	Rem.	—	—	2.0	—	—	—	—	—	1420 (771)	1640 (893)	1600–1800 (871–982)
	BAg-18	P07600	60	Rem.	10	—	—	10	—	—	—	—	1115 (602)	1325 (718)	1325–1550 (718–843)
	BAg-19	P07925	92	Rem.	—	—	—	—	0.2	—	—	—	1400 (760)	1635 (891)	1610–1800 (877–982)
	BAg-20	P07301	30	38	32	—	—	—	—	—	—	—	1250 (677)	1410 (766)	1410–1600 (766–871)
	BAg-21	P07630	63	28	—	—	2.5	6	—	—	—	—	1275 (691)	1475 (802)	1475–1650 (802–899)
	BAg-24	P07505	50	20	28	—	2.0	—	—	—	—	—	1220 (660)	1305 (705)	1305–1550 (708–843)
	BAg-26	P07250	25	38	33	—	2.0	—	—	—	—	—	1305 (705)	1475 (802)	1475–1600 (800–870)
	BAg-27	P07251	25	35	26	14	—	2	—	—	—	—	1125 (605)	1375 (745)	1375–1575 (745–860)
	BAg-28	P07401	40	30	28	—	—	—	—	—	—	—	1200 (649)	1310 (710)	1310–1550 (710–843)
	BAg-33	P07252	25	30	28	18	—	2	—	—	—	—	1125 (607)	1260 (682)	1260–1400 (681–760)
	BAg-34	P07380	38	32	28	—	—	2	—	—	—	—	1200 (649)	1330 (721)	1330–1550 (721–843)
	BVAg-6b	P07507	50	Rem.	—	—	—	—	—	—	—	—	1435 (779)	1602 (872)	1600–1800 (871–982)
	BVAg-18	P07607	60	Rem.	—	—	—	10	—	—	—	—	1115 (602)	1325 (718)	1325–1550 (718–843)
	BVAg-29	P07627	62	Rem.	—	—	—	—	—	—	—	14	1155 (624)	1305 (708)	1305–1450 (708–788)
	BVAg-31	P07587	58	32	—	—	—	—	—	—	Rem.	—	1515 (824)	1565 (852)	1565–1625 (852–885)
	BVAg-32	P07547	54	21	—	—	—	—	—	—	Rem.	—	1650 (899)	1740 (950)	1740–1800 (950–982)

(Continued)

Table 15.5 (Continued)
Filler Metal (FM) Groups

FM-No.	AWS Classification	UNS No.	Approximate Chemical Composition, Weight Percent (wt %)					Solidus °F (°C)	Liquidus °F (°C)	Brazing Temperature °F (°C)
			Au	Cu	Pd	Ni				
120	BAu-1	P00375	37	Rem.	—	—		1815 (991)	1860 (1016)	1860–2000 (1016–1093)
	BAu-2	P00800	80	Rem.	—	—		1635 (891)	1635 (891)	1635–1850 (891–1010)
	BAu-3	P00350	35	Rem.	—	3		1785 (974)	1885 (1029)	1885–1995 (1029–1091)
	BAu-4	P00820	82	—	—	Rem.		1740 (949)	1740 (949)	1740–1840 (950–1005)
	BAu-5	P00300	30	—	34	36		2075 (1135)	2130 (1166)	2130–2250 (1166–1232)
	BAu-6	P00700	70	—	8	22		1845 (1008)	1915 (1047)	1915–2050 (1047–1122)
	BVAu-2	P00707	80	Rem.	—	—		1635 (891)	1635 (891)	1635–1850 (891–1010)
	BVAu-4	P00827	82	—	—	Rem.		1740 (949)	1740 (949)	1740–1840 (949–1004)
	BVAu-7	P00507	50	—	Rem.	25		2015 (1102)	2050 (1121)	2050–2110 (1121–1154)
	BVAu-8	P00927	92	—	Rem.	—		2190 (1200)	2265 (1240)	2265–2325 (1240–1274)
			Pd	Co						
130	BVPd-1		65	Rem.				2245 (1230)	2255 (1235)	2255–2285 (1235–1252)
			Al	Si	Cu	Mg	Other			
140	BAlSi-2		Rem.	7	—	—	—	1070 (577)	1142 (617)	1110–1150 (599–621)
	BAlSi-3		Rem.	10	4	—	—	970 (521)	1085 (585)	1060–1120 (571–604)
	BAlSi-4		Rem.	12	—	—	—	1070 (577)	1080 (583)	1080–1120 (577–605)
	BAlSi-5		Rem.	10	—	—	—	1070 (577)	1110 (599)	1090–1120 (588–604)
	BAlSi-7		Rem.	10	—	1.5	—	1038 (559)	1105 (596)	1090–1120 (588–604)
	BAlSi-9		Rem.	12	—	0.3		1044 (562)	1080 (582)	1080–1120 (582–604)
	BAlSi-11		Rem.	10	—	1.5	0.1 Bi	1038 (559)	1105 (596)	1090–1120 (588–604)
			Cu	P	Ag					
150	BCuP-1	C55180	Rem.	5	—			1310 (710)	1695 (924)	1450–1700 (788–927)
	BCuP-2	C55181	Rem.	8	—			1310 (710)	1460 (793)	1350 –1550 (732–843)
	BCuP-3	C55281	Rem.	6	5			1190 (643)	1495 (813)	1325–1500 (718–816)
	BCuP-4	C55283	Rem.	7	6			1190 (643)	1325 (718)	1275–1450 (691–788)
	BCuP-5	C55284	Rem.	5	15			1190 (643)	1475 (802)	1300–1500 (704–816)
	BCuP-6	C55280	Rem.	7	2			1190 (644)	1440 (760)	1300–1500 (705–816)
	BCuP-7	C55282	Rem.	7	5			1190 (643)	1420 (771)	1300–1500 (704–816)

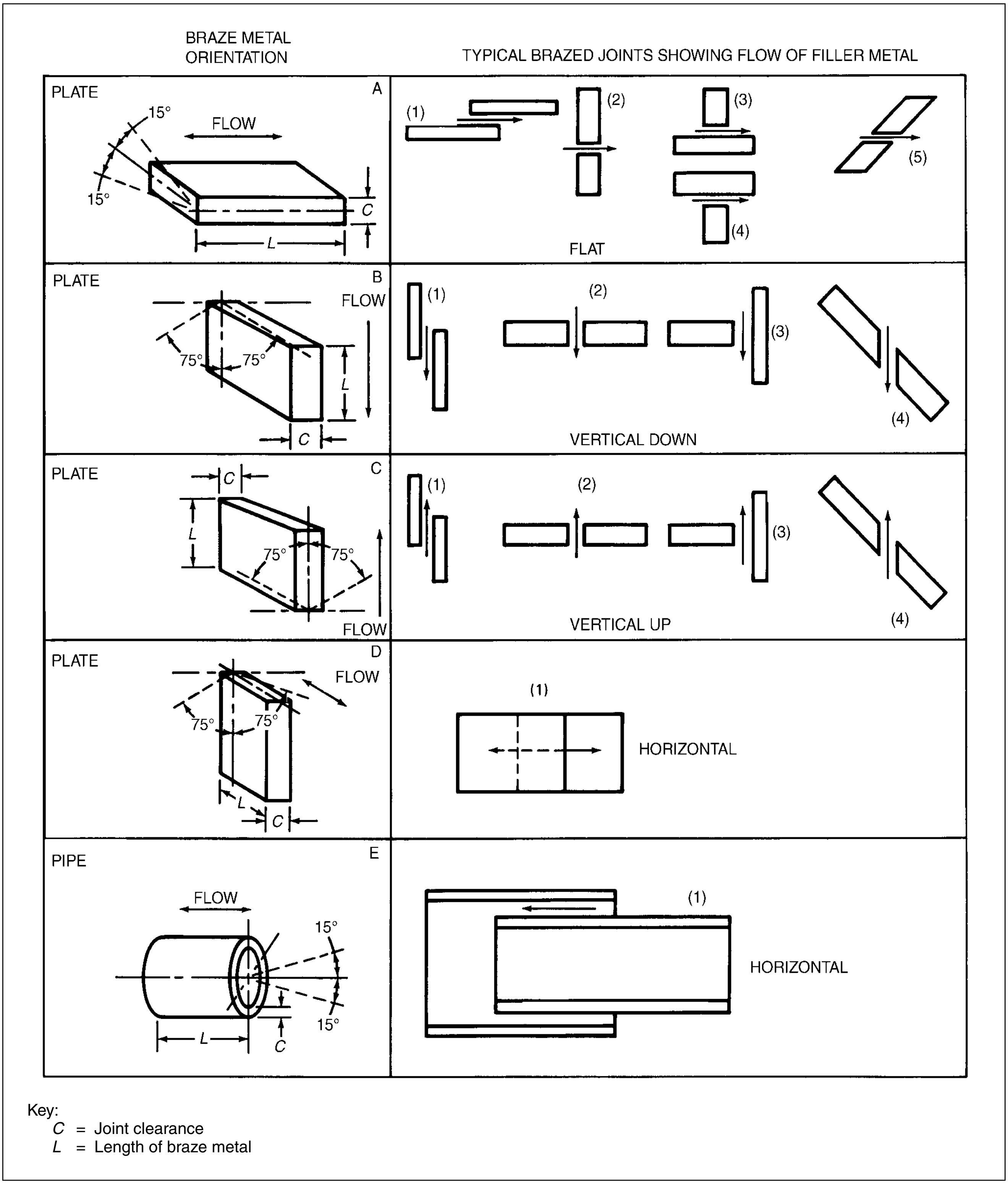
(Continued)

Table 15.5 (Continued)
Filler Metal (FM) Groups

FM-No.	AWS Classification	UNS No.	Approximate Chemical Composition, Weight Percent (wt %)								Solidus °F (°C)	Liquidus °F (°C)	Brazing Temperature °F (°C)
			Cu	P									
160	BCu-1	C14180	99.9	0.1							1981 (1083)	1981 (1083)	2000–2100 (1093–1149)
	BCu-1a	—	99.0	—							1981 (1083)	1981 (1083)	2000–2100 (1093–1149)
	BCu-2	—	86(a)	—							1981 (1083)	1981 (1083)	2000–2100 (1093–1150)
	BVCu-1x	C14181	100	—							1981 (1083)	1981 (1083)	2000–2100 (1093–1150)
			Cu	Zn	Sn	Fe	Mn	Ni	P				
170	RBCuZn-A	C47000	59	Rem.	0.5	—	—	—	—		1630 (888)	1650 (899)	1670–1750 (910–954)
	RbcuZn-C	C68100	58	Rem.	0.9	0.8	0.3	—	0.1		1590 (866)	1630 (888)	1670–1750 (910–954)
	RBCuZn-D	C77300	48	Rem.	—	—	—	10	0.2		1690 (921)	1715 (935)	1720–1800 (938–982)
			Ni	Cr	B	Si	Fe	C	P	Other			
180	BNi-1	N99600	Rem.	14	3	4	4	0.8	—		1790 (977)	1900 (1038)	1950–2200 (1066–1204)
	BNi-1a	N99610	Rem.	14	3	4	4	—	—		1790 (977)	1970 (1077)	1970–2200 (1077–1204)
	BNi-2	N99620	Rem.	7	3	4	3	—	—		1780 (971)	1730 (944)	1850–2150 (1010–1177)
	BNi-3	N99630	Rem.	—	3	4	—	—	—		1800 (982)	1900 (1038)	1850–2150 (1010–1177)
	BNi-4	N99640	Rem.	—	2	3	2	—	—		1800 (982)	1950 (1066)	1850–2150 (1011–1177)
	BNi-5	N99650	Rem.	19	—	10	—	—	—		1975 (1079)	2075 (1136)	2100–2200 (1149–1204)
	BNi-6	N99700	Rem.	—	—	—	—	—	11		1610 (877)	1610 (877)	1700–2000 (927–1093)
	BNi-7	N99710	Rem.	14	—	—	—	—	10		1630 (888)	1630 (888)	1700–2000 (927–1093)
	BNi-8	N99800	Rem.	—	—	7	—	—	—	23 Mn	1800 (982)	1850 (1010)	1850–2000 (1010–1093)
	BNi-9	N99612	Rem.	15	4	—	2	—	—	4 Cu	1930 (1055)	1930 (1055)	1950–2200 (1066–1204)
	BNi-10	N99622	Rem.	12	3	4	4	0.5	—	16 W	1780 (970)	2020 (1105)	2100–2200 (1150–1205)
	BNi-11	N99624	Rem.	10	3	4	3	0.4	—	12 W	1780 (970)	2003 (1095)	2100–2200 (1150–1204)
			Co	Cr	Ni	Si	Fe	C	P	Other			
190	BCo-1	R39001	Rem.	19	17	8	1	0.4	—	4 W	2050 (1120)	2100 (1149)	2100–2250 (1149–1232)
			Mg	Al	Zn								
200	BMg-1	M19001	Rem.	9	2						830 (443)	1110 (599)	1120–1160 (604–627)

(a) This composition requirement pertains only to the cuprous oxide powder and does not include requirements for the organic vehicle in which the cuprous oxide is suspended.

Source: Adapted from American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Appendix C, Table C1; SI conversions from AWS Committee on Filler Metal, 1992, *Specification for Filler Metals for Brazing and Braze Welding*, ANSI/AWS A5.8-92, Miami: American Welding Society.



Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Figure A1.

Figure 15.9—Brazing Positions for Procedure or Performance Qualification

PERFORMANCE QUALIFICATION

In addition to establishing a welding or brazing procedure specification and subsequently testing the procedure and recording the results on the procedure qualification record, it is also necessary to determine the ability of the welder, welding operator, brazer, or brazing operator to not only follow the welding procedure specification but also make a sound welded or brazed joint using the process and filler metals specified by the welding or brazing procedure specification.

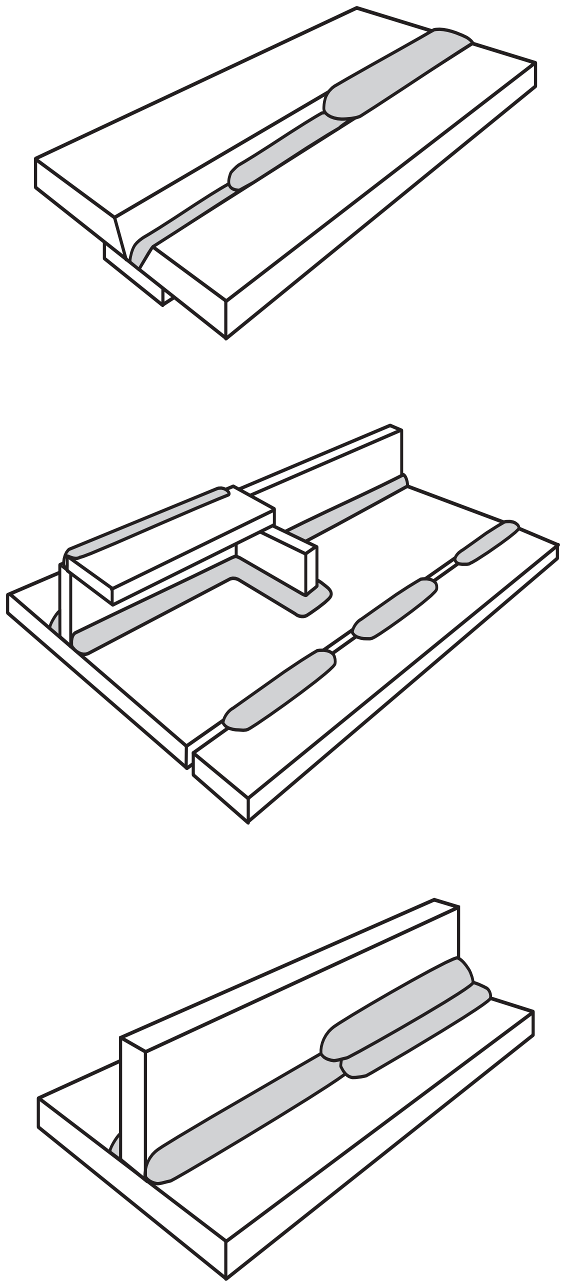
Welders or brazers perform manual or semiautomatic welding or brazing. Welding or brazing operators weld or braze using mechanized, automatic, or robotic equipment. Since the skills required to perform manual and semiautomatic welding and brazing are significantly different than those required to perform mechanized, automatic, or robotic welds and brazes, the codes require the qualification of an individual employing a process as a welder or brazer to be performed separately if the person is to weld or braze using the same process as an operator.

WELDERS AND WELDING OPERATORS

It may be advantageous to include workmanship test weldments in the qualification process in addition to the testing required by code. This may aid in determining the ability of some welders to produce acceptable welds. Some typical workmanship test weldments are presented in Figure 15.10.

Welder, welding operator, and tack welder qualification tests are used to determine the ability of the persons tested in producing sound welds or brazed joints using the given process, materials, and procedure. Qualification tests are not intended to be used as a guide for welding acceptability during construction, but rather to assess whether an individual has the required minimum level of skill to produce sound welds. It is important to note that these tests cannot predict how an individual will perform on a particular production weld. For this reason, complete reliance should not be placed on qualification testing. Instead, the quality of production welds should be determined by means of inspection during and following the completion of the welding.

Various codes, specifications, and governing rules prescribe similar methods for the qualification of welders, welding operators, and tack welders. The applicable code or specification should be consulted for specific details and requirements.



Note: The top figure illustrates a weldment intended to demonstrate ability to weld a groove weld with a backing strip. The center figure shows a weldment intended to demonstrate ability to weld fillet, corner, and square groove joints. The bottom figure shows a weldment intended to demonstrate ability to weld single and multipass fillet welds.

Source: AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society, Figure 3.2.

Figure 15.10—Typical Workmanship Test Weldments

Qualification Requirements

The responsibility for the qualification of welding personnel and procedures lies with the employer. Qualification requirements governing the welding of boilers, pressure vessels, piping systems, and structures typically require that each welder or welding operator (1) weld a test coupon to demonstrate his or her ability and (2) follow a welding procedure specification to make sound welds.

Each qualification weld is tested in a specific manner. Section IX of ASME's *1998 Boiler and Pressure Vessel Code* specifies that test coupons or production welds are to be examined using a bend test or radiography.[53]

Qualification requirements for the welding of pressure pipe differ from those for welding plate or structural members. The principle difference is the type of test assemblies used. These tests require the use of pipe assemblies instead of flat plate. The test positions also differ to some extent. Space restrictions may also be included as a qualification factor if the production work involves welding in areas with restricted access. Figures 15.1 and 15.2 illustrate the different positions and the type of tests that may be implemented for the qualification of the welders of groove welds.

Limitation of Variables

Welding conditions that affect the welder or welding operator's ability to produce sound welds are considered *qualification variables*. When a welder takes a test under a certain set of conditions (welding process, material, thickness, position, progression backing electrode or filler metal type, and so on), the variables in the code define the range of welding conditions that the welder is qualified to make in production welding. A welder or welding operator must be requalified if the production welding condition are beyond the limits for which he or she was qualified.

Discussed below are qualification variables specified in the American National Standard *Structural Welding Code—Steel*, AWS D1.1:2000.[54] These require the requalification of the welder or welding operator should these variables be exceeded.

Welding Process. A change in the welding process—from shielded metal arc welding to gas metal arc welding, for example—requires the requalification of the welder or welding operator since the skills needed to use one welding process are different from the skills needed to use another.

Filler Metal. Filler metals used in welding are grouped based on their usability characteristics. These groups are assigned F-numbers. Table 15.6 lists typical F-number assignments. Ordinarily, a welder is required to qualify using a filler metal that has an F-number that is the same as the one that is to be used in production. A common exception to this rule occurs with submerged arc welding electrodes F-1 through F-4; in these cases, qualification with an electrode that has a higher F-number entails qualification with electrodes having a lower F-number.

The American Welding Society allows some flexibility in the use of filler metals in production, depending upon the type of filler that was used during the welder qualification test. Table 15.6 lists alternate F-numbers.[55] It demonstrates that if a certain grade of filler metal is used for qualification, then the welder is also qualified to use a lower grade of filler metal without requalification.

Table 15.6
Allowable Filler Metals for Performance Qualification

Filler Metal Used in Qualification Test	Qualifies the Welder to Use the Filler Metal Listed Below
F-Numbers 1 through 5	The F-number used in the test and any lower F-number
F-Number 6*	All F-Number 6 filler metals
F-Numbers 21 through 25	All F-Number 2X filler metals
F-Numbers 31 through 36	Only for the specific 3X F-Number filler metal
F-Number 41 through 45	F-Numbers 1 through 5 and all F-Number 4X
F-Number 51 through 55	All F-Number 5X filler metals
F-Number 61	All F-Number 61 filler metals
F-Number 71	Only for the specific F-Number 71 filler metal
F-Number 81	All F-Number 91 filler metals

*Deposited solid bare wire that is not covered by an AWS specification but which conforms to an A-Number analysis in Annex C, Table C2 of AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society, may be considered classified as F-Number 6.

Source: Adapted from AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society, Table 3.4.

53. See Reference 35.
54. See Reference 34.

55. These alternate electrodes are dependent upon the group of electrodes used during performance qualification. Table 3.1 in American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society lists prequalified base metal-filler metal combinations for matching strength.

Welding Position. Welding test positions are defined differently for plate and pipe (see Figures 15.1 and 15.2). A change in welding position from that qualified may require requalification; however, certain test positions qualify for more than one production welding position (e.g., qualification in the 3G position qualifies the welder for the vertical and flat positions). Table 15.7 lists the various testing positions and the corresponding production welding positions qualified by those test positions. The rotational limits for the production welding positions are shown in Figures 15.3 and 15.4 for groove and fillet welds, respectively.

The term *technique* refers to the way the welder applies the filler metal. Some welding electrodes can be used only uphill or downhill, whereas others can be used uphill and downhill. In vertical position welding, for example, a change in welding progression from uphill to downhill would require requalification.

To accommodate work performed in positions other than flat welding, codes and specifications usually require that welder qualification tests be performed in one or more of the most difficult welding positions encountered in production. Qualification in a more difficult position qualifies the welder for the less difficult positions. Table 15.7 demonstrates that successful testing on a pipe with a groove weld in the 1G position leads to qualification for flat welding only. Passing a similar test in the 6G position results in qualification for groove and fillet welds in all positions.

Joint Backing. Joint backing includes any material placed at the root of the weld to support the liquid weld pool. Welds made with backing include those made on metal backing strips and nonmetallic or nonfusing metal back-up bars, root welds created with another welding process, welds made from both sides, and fillet welds.

If a welder qualifies using backing on the test coupon, but the backing is removed for production welding for a joint made from one side, the welder must normally requalify. If a welder qualifies using a joint made from one side without backing, he or she may weld on a joint that has backing without requalification. Figure 15.11 shows a test plate of groove welds of limited thickness with backing. Figure 15.12 shows a test plate of groove welds on 1 in. (25 mm) thick plate with backing.[56]

Test Coupon Thickness. The thickness of the production work determines the thickness of the plate or pipe test coupon to be welded. It is necessary to determine the thickness of the production work carefully so that requalification does not become necessary when it is discovered that a material that must be welded is thicker than that which the welder is qualified to weld. The rule of thumb is that a welder is qualified to deposit in production welding two times the thickness of the weld he or she deposited on the test coupon. That is, if a welder made a weld that was 3/8 inch (in.) (9 millimeters [mm]) thick on the test coupon, he or she is allowed to make welds that are 3/4 in. (19 mm) thick in production.

However, the codes recognize that once a welder makes a weld of a given thickness on the test coupon, no further information is obtained about his or her skill by requiring him or her to make thicker and thicker test coupons. Accordingly, depending on the code, once a welder makes a weld that is 1/2, 3/4, or 1 in. thick, he or she is qualified to weld all thicknesses.

It should be noted that when working with Section IX of the ASME *Boiler and Pressure Vessel Code,*[57] the weld deposit thickness determines the thickness of weld metal the welder is allowed to use in production, not the thickness of the base metal in the test coupon. It should also be noted that when a welder welds on a test coupon using more than one process or types of filler metal, the thickness of the weld he or she may weld in production with any given process or type of filler metal depends on the deposit thickness for the process and the type of filler metal that was used on the test coupon.

Test Specimens

Typical groove weld qualification tests for limited thickness are illustrated in Figure 15.11. The qualification groove weld plates for unlimited thickness, shown in Figure 15.12, are essentially the same, except that the plate thickness is increased. After successful testing, the welder is qualified to weld limited thicknesses, usually up to two times (2T) the thickness of the test weld.

The joint details of groove weld qualification tests for butt joints on pipe or tubing should be in accordance with a qualified welding procedure specification for single-V welded pipe butt joints. As an alternative, the joint details shown in Figure 15.12 are frequently used. The publication *Structural Welding Code—Steel,* AWS D1.1:2000,[58] provides a special joint design for the qualification of welders to weld T-, K-, or Y-connections in pipe. This is identified as the 6GR Test Joint.

Groove weld qualification usually qualifies a welder to weld both fillet and groove welds in the qualified positions. Fillet weld qualification limits the welder to fillet welding in the position qualified and other specified positions with lesser difficulty only. Common limitations with respect to type and position are presented in Figure 15.4.

56. Table 4.9 in American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel,* AWS D1.1:2000, Miami: American Welding Society and Table QW-461.9 in American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, Subcommittee on Welding, 1998, *Welding and Brazing Qualifications,* Section IX of 1998 *Boiler and Pressure Vessel Code,* New York: American Society of Mechanical Engineers provide qualified positions and limitations as a result of performance qualification tests.

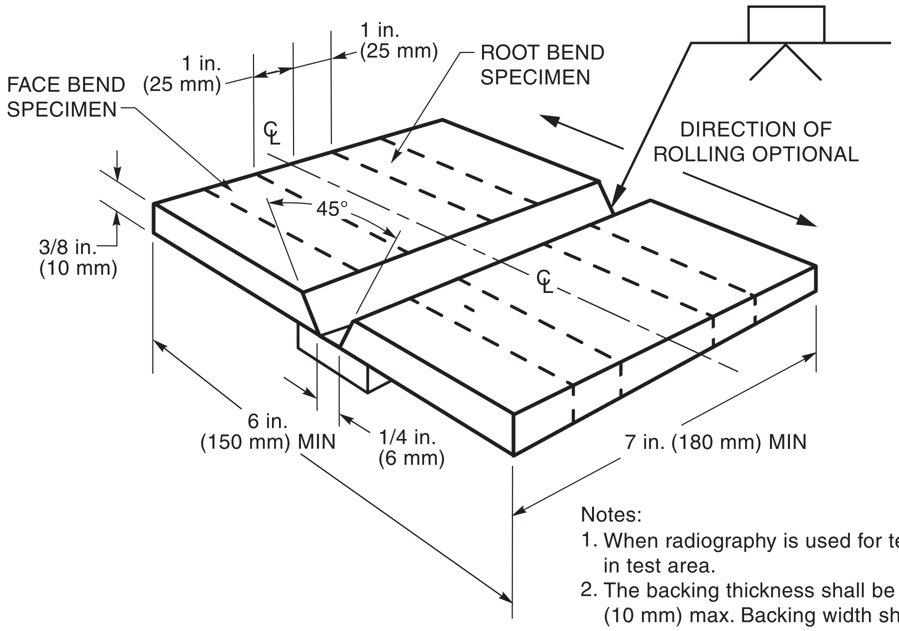
57. See Reference 21.
58. See Reference 34.

Table 15.7
Performance Qualification—Position and Diameter Limits

Qualification Test		Position and Type of Weld Qualified*			
		Groove			
Weld	Position*	Plate; Pipe over 24 in. (600 mm) Dimension (O.D.)†	Pipe ≤ 24 in. (600 mm) O.D.†	Fillet Plate and Pipe†	Clad and Hardfacing Plate and Pipe‡
Plate—Groove	1G	F	—	F	—
Sheet—Groove	2G	F, H	—	F, H	—
	3G	F, V	—	F, H, V	—
	4G	F, O	—	F, H, O	—
	3G and 4G	F, V, O	—	All	—
	2G, 3G, and 4G	All	—	All	—
Plate—Fillet	1F	—	—	F	—
Sheet—Fillet	2F	—	—	F, H	—
	3F	—	—	F, H, V	—
	4F	—	—	F, H, O	—
	3F and 4F	—	—	All†	—
Pipe—Groove§,∞	1G	F	F	F	—
	2G	F, H	F, H	F, H	—
	5G	F, V, O	F, V, O	All	—
	6G	All	All	All	—
	2G and 5G	All	All	All	—
Pipe—Fillet	1F	—	—	F	—
	2F	—	—	F, H	—
	2FR	—	—	F, H	—
	4F	—	—	F, H, O	—
	5F	—	—	All	—
Clad or hardfacing# (Pipe or plate)‡	1C	—	—	—	F
	2C	—	—	—	F, H
	3C	—	—	—	F, V
	4C	—	—	—	F, O
	3C and 4C	—	—	—	F, V, O
	2C, 3C, and 4C	—	—	—	All
	5C (pipe only)	—	—	—	F, V, O
	6C (pipe only)	—	—	—	All

* For definitions of these welding test positions, refer to Annex B in AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society.
† F = flat; FR = flat position rotated; H = horizontal; V = vertical; and O = overhead.
‡ For surfacing applications, qualification on plate qualifies for plate only except that qualification on plate in the flat position also qualifies on pipe in the flat position. Qualification on pipe in any position shown above for cladding or hardfacing also qualifies for plate in the positions allowed in the table.
§ Welders qualified on tubular product forms may weld on tubular, plate, and sheet in accordance with any restrictions on diameter contained in AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society.
∞ Refer to Table 3.6 in AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society.
Positions for surfacing applications are defined as 1C = flat; 2C = horizontal; 3C = vertical; 4C = overhead; 5C = circumferential pipe horizontal position; and 6C = circumferential pipe joint with pipe inclined 45°.

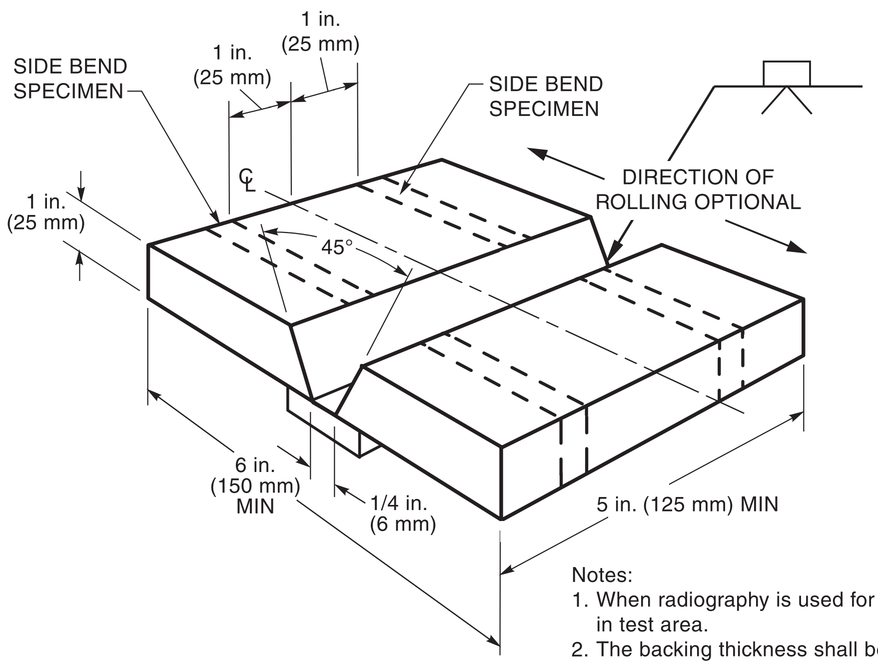
Source: Adapted from AWS Committee on Welding Qualification, 1998, *Specification for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1:1998, Miami: American Welding Society, Table 3.5.



Notes:
1. When radiography is used for testing, no tack welds shall be in test area.
2. The backing thickness shall be 1/4 in. (6 mm) min to 3/8 in. (10 mm) max. Backing width shall be 3 in. (75 mm) min when not removed for radiography; otherwise 1 in. (25 mm) min.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Figure 4.30.

Figure 15.11—Test Plate for Limited Thickness—All Positions—Welder Qualification



Notes:
1. When radiography is used for testing, no tack welds shall be in test area.
2. The backing thickness shall be 1/4 in. (6 mm) min to 3/8 in. (10 mm) max. Backing width shall be 3 in. (75 mm) min when not removed for radiography; otherwise, 1 in. (25 mm) min.

Source: Adapted from American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Figure 4.21.

Figure 15.12—Test Plate for Unlimited Thickness—Welder Qualification

Testing of Qualification Welds

All codes and specifications establish the extent of the testing that is to be performed on qualification welds as well as the acceptance criteria. For groove welds, guided bend specimens are cut from specific locations on the test weldment, and they are bent over a specified radius. The maximum permissible flaw size is typically 1/8 in. As fillet welds do not readily lend themselves to guided bend tests, fillet weld break tests or macroetch tests, or both, are required in most cases. Radiographic testing may be permitted as an alternative to mechanical or other testing methods.

Qualification Records

The responsibility for the qualification of welding personnel and procedures lies with the employer who is responsible for production welding. After the successful qualification of a welder or welding operator, the employer is required to prepare a welder performance qualification record. This record documents the qualification details, including the essential variables that were followed during the welding of the test coupon, the test results, and a statement of certification that the testing was performed in accordance with the applicable code. Because qualification records are certified by the employer, it is common practice to refer to a welder who has passed a qualification test as a *certified welder* rather than a *qualified welder.*

Most codes consider a person who has welded a procedure qualification test coupon to be qualified as a welder or operator as well. However, the base metals, filler metals, positions, thicknesses, and other conditions for which this welder is qualified are based on the rules for welder qualification rather than on the rules for procedure qualification. A typical welder qualification record is presented in Figure 15.13.

Duration of Qualification

The duration of the validity of the qualification of a welder or welding operator depends on the limits of the code or standard under which he or she is qualified. Most codes require that the welder use each welding process for which he or she is qualified at least once every six months; otherwise, his or her qualification for that process expires. Most codes allow qualifications to be extended indefinitely provided the qualified welder or welding operator performs satisfactory work using the welding processes within the period stated in the standard.

BRAZERS AND BRAZING OPERATORS

The purpose of brazer and brazing operator performance qualification testing is to verify the ability of brazers to produce sound brazed joints. Brazing operators are tested to verify their ability to operate torch, furnace, or induction brazing equipment in accordance with a brazing procedure specification.

Two standards that address brazing performance qualifications are *Brazing Procedure and Performance Qualification,* ANSI/AWS B2.2,[59] and Part QB of *Welding and Brazing Qualifications*, Section IX of the ASME *Boiler and Pressure Vessel Code.*[60]

Acceptance Criteria

Brazers and brazing operators are required to produce one or more test samples following a qualified brazing procedure. The acceptance of performance brazements is based on visual examination or specimen testing. Qualification by means of brazing and testing specimens qualifies the individual to perform production brazing based on the conditions and the essential variables for performance qualification in the applicable code or standard that is being followed.

Qualification by Visual Examination. Qualification by visual examination is accomplished with a test brazement that is representative of the design details of the joint to be brazed in production. Typical workmanship test brazements are shown in Figure 15.14. The completed brazement must meet the requirements of the standard.

Qualification by Specimen Testing. Either a standard test brazement or a workmanship test brazement can be used for qualification by specimen testing. A standard test brazement in plate or pipe may have a butt, scarf, lap, single- or double-spliced butt, or a rabbet joint, as shown in Figure 15.15.

After completion of the test brazement, the test joint is normally sectioned. The exposed surfaces are then polished and etched, and the brazed joint is examined at low magnification (e.g., 3X) for discontinuities. Peel tests may be used in lieu of section tests, or vice versa, for lap or spliced butt joints. In the latter case, the brazed joints are peeled apart, and the bond area is examined visually. The macroetched cross sections or the peeled surfaces must meet the acceptance criteria of the appropriate standard.

59. See Reference 26.
60. See Reference 35.

WELDER, WELDING OPERATOR, OR TACK WELDER QUALIFICATION TEST RECORD

Type of Welder ______________________
Name ______________________ Identification No. ______________
Welding Procedure Specification No. ____________ Rev ____________ Date ____________

Variables	Record Actual Values Used in Qualification	Qualification Range
Process/Type [Table 4.10, Item (1)]		
Electrode (single or multiple) [Table 4.10, Item (8)]		
Current/Polarity		
Position [Table 4.10, Item (4)]		
Weld Progression [Table 4.10, Item (6)]		
Backing (YES or NO) [Table 4.10, Item (7)]		
Material/Spec.	to	
Base Metal		
Thickness: (Plate)		
Groove		
Fillet		
Thickness: (Pipe/tube)		
Groove		
Fillet		
Diameter: (Pipe)		
Groove		
Fillet		
Filler Metal [Table 4.10, Item (3)]		
Spec. No.		
Class		
F-No. [Table 4.10, Item (2)]		
Gas/Flux Type [Table 4.10, Item (3)]		
Other		

V[illegible]ON (4.8.1)
Acc[illegible]S or NO _____

[illegible]uided B[illegible]est Results (4.30.5)

Type	Result	Type	Result

[illegible]et Test Results (4.30.2.3 and 4.30.4.1)

Appearance ______________ Fillet Size ______________
Fracture Test Root Penetration ______________ Macroetch ______________
(Describe the location, nature, and size of any crack or tearing of the specimen.)

Inspected by ______________ Test Number ______________
Organization ______________ Date ______________

RADIOGRAPHIC TEST RESULTS (4.30.3.1)

Film Identification Number	Results	Remarks	Film Identification Number	Results	Remarks

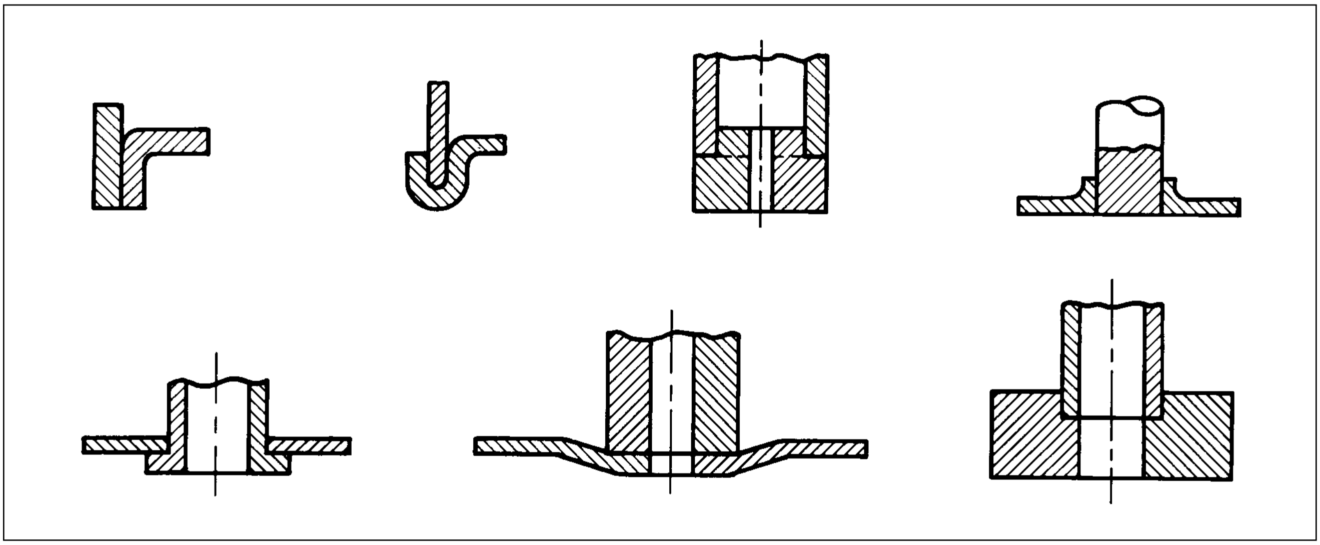
Interpreted by ______________ Test Number ______________
Organization ______________ Date ______________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of AWS D1.1, (__________) Structural Welding Code—Steel.
(year)

Manufacturer or Contractor ______________ Authorized By ______________
Form E-4 Date ______________

Source: American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society, p. 307.

Figure 15.13—Sample Welder Performance Qualification (WPQ) Record Form



Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Figure 2.

Figure 15.14—Typical Workmanship Brazements

Qualification Variables

Typical brazing performance qualification variables that may require requalification if changed are the following:

1. Brazing process,
2. Base metal,
3. Base metal thickness,
4. Brazing filler metal composition,
5. Method of adding filler metal,
6. Brazing position (see Figure 15.9), and
7. Joint design.

To minimize the number of brazing performance qualification tests, base metals are separated into groups that have similar brazeability (see Table 15.3). Brazing filler metals are grouped according to similarity of composition or melting range (see Table 15.4).

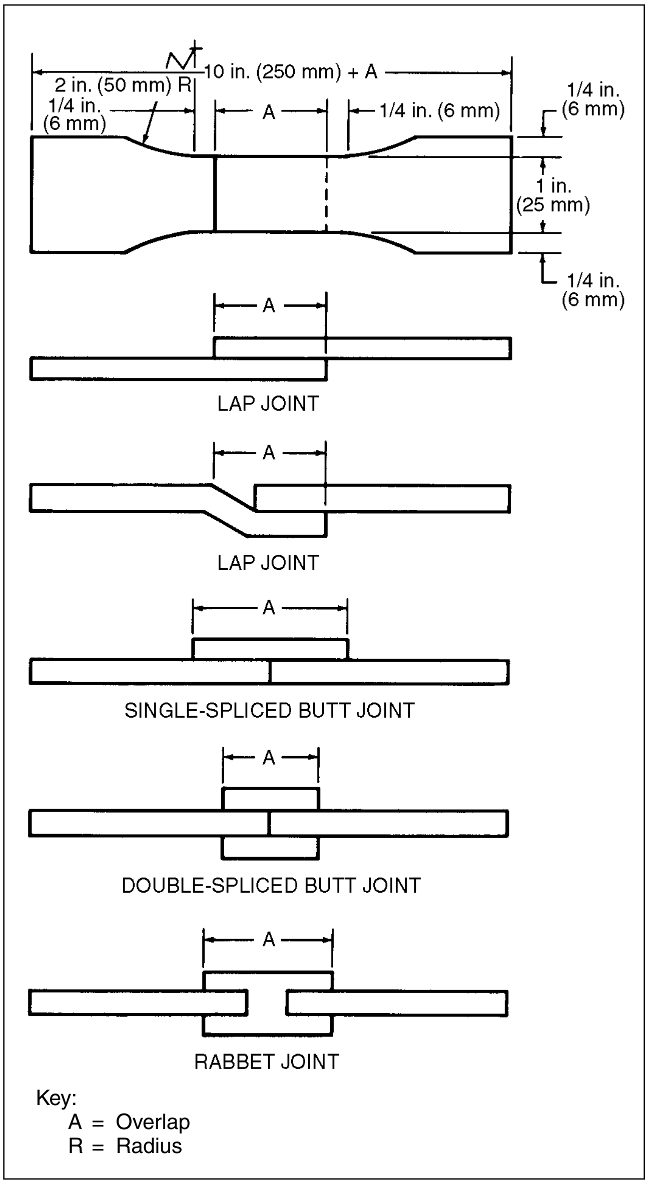
Performance Qualification Test Record

The brazing of the test brazement and the results of the acceptance tests are reviewed by the individual responsible for the test. The information is then recorded on a brazer performance qualification test record form. A sample form that addresses brazing variables is shown in Figure 15.16. Alternate test forms are also available in *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2.[61]

THERMAL SPRAY OPERATORS

The operators of equipment used to apply thermal spray coatings are qualified for each thermal spray process. Both a welding procedure specification and a procedure qualification record are established by the manufacturer. Thermal spray operators must be qualified for a specific coating process and method of application as described in the welding procedure specification. They can be qualified using the recommended procedures in *Guide for Thermal Spray Operator Qualification*, ANSI/AWS C2.16.[62] They should also be qualified to the specific requirements of the materials, position, and other essential variables identified by code.

61. See Reference 26.
62. American Welding Society (AWS) Committee on Thermal Spraying, *Guide for Thermal Spray Operator Qualification*, ANSI/AWS C2.16, Miami: American Welding Society.



Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Figure A2B.

Figure 15.15—Tensile Specimens for Brazed Lap Joints, Spliced Butt Joints, and Rabbet Joints

Acceptance Criteria

Initial thermal spray operator qualification testing consists of the following:

1. A written test covering all aspects of the coating process and application method,
2. Demonstration of the ability to operate the equipment,
3. Testing to determine knowledge of the proper masking procedures for both surface preparation and spraying, and
4. Surface preparation of the thermal spray test specimens.

Test specimens should be prepared from alloys specified by the purchaser and agreed to by the certifying agent. The type and number of tests should be specified in the contract documents. The testing conditions and results of the test are recorded and certified by the representative who observed the tests.

NONDESTRUCTIVE EXAMINATION PERSONNEL

The qualification of personnel is one of the most important aspects of the field of nondestructive examination. As in welding and brazing, nondestructive examination (NDE) qualification assures that the individual performing the test method has the proper knowledge and experience to implement the test and interpret the results. Most personnel are qualified in accordance with the American Society for Nondestructive Testing's (ASNT) *Recommended Practice No. SNT-TC-1A*.[63] This document establishes guidelines for the education, training, experience, and testing requirements for various levels of competence. Certification is granted in three qualification levels, which are described below.

Radiographic testing personnel must be qualified according to the health and safety criteria specified by the Nuclear Regulatory Commission (NRC) or local state regulatory control board, depending upon jurisdiction in the state. State boards and the NRC list individuals by a letter amending the company's isotope license, or they may list qualified individuals on the license itself. This certification addresses the individual's ability to complete successfully the training and examinations specified in the company's operating and emergency manuals only; it is not related to the employee's ability to produce high-quality radiographs.

Level I Qualification

Level I personnel are qualified to perform specific calibrations, tests, and evaluations according to written instructions and to record the results. They receive the

63. American Society for Nondestructive Testing (ASNT), *Recommended Practice No. SNT-TC-1A,* Columbus, Ohio: American Society for Nondestructive Testing.

Form A3

BRAZING PERFORMANCE QUALIFICATION RECORD

Name ____________________ Id. ____________________

Date ____________________ BPS No. ____________________

Brazing Process ____________________ Brazer ☐ Operator ☐

TEST BRAZEMENT

Base Metal Id. __________ BM No. __________ BM T __________

Filler Metal Id. __________ FM No. __________ FM Feed __________

Test Position __________ Joint Type ____________________

Other ____________________

TEST RESULTS

VISUAL	Pass	Fail

MACROETCH OR PEEL

Specimen No.	Remarks	Pass	Fail

QUALIFIED FOR

Brazing Process ____________________ Position ____________________

BM No. ____________________ BM T ____________________

FM No. ____________________ FM Feed ____________________

Joint Type ____________________

Other ____________________

The above named individual is qualified in accordance with the American Welding Society *Standard for Brazing Procedure and Performance Qualification,* ANSI/AWS B2.2-91.

Date ____________________

Signed ____________________
Qualifier

Source: American Welding Society (AWS) Committee on Welding Qualification, 1991, *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2-91, Miami: American Welding Society, Appendix A, Form A3.

Figure 15.16—Suggested Format for Brazer/Brazing Operator Performance

necessary guidance or supervision from a supervisor who is certified at Level II or III.

Level II Qualification

Level II personnel are qualified to set up and calibrate equipment and to interpret and evaluate results with respect to applicable codes, standards, and specifications. They must (1) be thoroughly familiar with the scope and limitations of the method, (2) exercise responsibility for on-the-job training and the guidance of trainers and Level I personnel, and (3) organize and report on nondestructive testing investigations.

Level III Qualification

Personnel certified for Level III are capable of and responsible for (1) establishing nondestructive examination techniques, (2) interpreting codes, standards, and specifications, and (3) designating the particular test method and technique to be used in testing. They are accountable for the complete nondestructive examination operation and the evaluation of all test results. It is desirable that Level III personnel have a general familiarity with all commonly used NDE methods. They may also be responsible for the training and examination of Level I and Level II personnel for certification.

WELDING INSPECTORS

The objective of the welding inspector qualification program is to establish the knowledge and experience requirements of welding inspectors, who inspect weldments or welded products in accordance with codes or other requirements. The American Welding Society conducts examinations to certify Senior Welding Inspectors (SCWIs), Certified Welding Inspectors (CWIs), and Certified Associate Welding Inspectors (CAWIs) in accordance with *Standard for AWS Certification of Welding Inspectors,* AWS QC1.[64] It should be noted that although these examinations are designed to test a level of knowledge specified by the qualification standard, they do not necessarily reflect the level of competence required for each and every code or specification used in the welding fabrication field. Employers must recognize their responsibility to provide additional training and education for their welding inspectors, when needed, to satisfy current production needs and the requirements of new standards and specifications.

A Senior Certified Welding Inspector performs inspection, supervises inspection, develops procedures, and evaluates the performance of the personnel under his or her charge. A Certified Welding Inspector performs inspections and verifies that the work and records conform to all applicable codes and specifications. A Certified Associate Welding Inspector (CAWI) performs inspections under the direction of a CWI. However, the CWI alone is responsible for determining whether weldments conform to workmanship and acceptance standards.

Acceptance Criteria

Prospective inspectors must possess the required minimum visual, educational, and work qualifications directly related to weldments fabricated according to a code or specification. The individual's work experience must include one or more of the following:

1. Design of weldments,
2. Production welding,
3. Inspection of welds, and
4. Weld inspection and repair.

Candidates for AWS certification are also required to pass written tests in the following areas:

1. One of a number of specified codes and specifications;
2. Principles of welding, nondestructive testing, materials, heat treatment, and other fundamentals; and
3. Practical application of welding inspection.

Upon successful completion of the examination, the American Welding Society issues a certificate to the applicant indicating the level of certification granted. Certification must be renewed periodically by meeting certain requirements with or without re-examination.

STANDARDIZATION OF QUALIFICATION REQUIREMENTS

The two principal reasons for standardization in any field are public safety and economics, particularly as they affect the consumer. Increasing concern for the protection of consumer interest and remaining competitive in a global market make it imperative that standards be developed on a voluntary consensual basis with the representation of all affected interests.

Standardization in the field of welding qualification could lead to significant cost savings. Although most welding qualification standards differ only slightly, separate qualification is required for each. The resulting

64. See Reference 27.

duplication of effort and cost is counterproductive in the fabrication and construction industries and results in notable cost increases with no related benefits to the consumer.

The American Welding Society (AWS) is addressing this concern through several initiatives. The Welding Inspector Qualification and Certification Program has been created to promote the standardization of inspector qualification. In addition, the American Welding Society, in cooperation with the Edison Welding Institute (EWI) and The Welding Institute of England (TWI), has introduced a program to standardize proficiency for nondestructive examination personnel. This program requires independent testing and uniform criteria for the evaluation of nondestructive examination personnel. Moreover, two general qualification standards, *Standard for Welding Procedure and Performance Qualification*, ANSI/AWS B2.1,[65] and *Standard for Brazing Procedure and Performance Qualification*, ANSI/AWS B2.2,[66] are designed to provide single standards to replace several different standards containing similar rules for qualification of procedures and performance.

CONCLUSION

The widespread use of the computer has made the preparation of welding procedures and the documentation of test results much more efficient and convenient. A number of computer programs are available to facilitate the recording and tracking of welding procedure specifications, procedure qualification records, and welder and welding operator performance qualifications. Based on Section IX of the ASME *1998 Boiler and Pressure Vessel Code*,[67] the American Welding Society's *ArcWorks Section IX*™ is one such software package. National codes and standards are also available in compact disc format. These electronic versions feature search and cross-referencing capabilities that facilitate the location of the desired passages.

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65. See Reference 25.
66. See Reference 26.
67. See Reference 35.
68. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

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CHAPTER 16

CODES AND OTHER STANDARDS

Photograph courtesy of Boeing Defense & Space Group

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Contents

CHAPTER 16

CODES AND OTHER STANDARDS

INTRODUCTION

This chapter is intended to familiarize the fabricators and consumers of welded products with the basic documents that govern or guide welding activities. These documents serve to assure that safe and reliable welded products are produced and that the individuals associated with welding operations are not exposed to undue danger or other conditions that would be harmful to their health. Publications relating only to the manufacture of welding equipment are not addressed in this chapter. However, these publications may be referenced in codes and other standards, and their relationship to safety and reliability should not be underestimated.

Codes and other standards offer distinct benefits to the welding industry. These include promoting greater compatibility and interoperability of goods and services, enhancing of product quality and reliability at a reasonable price, and simplifying products for improved usability and ease of maintenance. This chapter describes some of the organizations that contribute to these benefits through the development of welding standards. Inasmuch as the globalization of the manufacturing and construction markets is broadening the range of inspection standards that might be specified for a product, this chapter has been expanded to include more of the international organizations that develop such standards.

The number as well as the scope of welding-related regulating documents grows on a daily basis. For example, a recent survey of International Organization for Standardization (ISO) welding standards lists 64 standards that apply directly to inspection issues related to welded structures alone. These standards are distributed among 22 management elements, which span the entire life of a structure, from its initial planning to record retention for the life of the structure. New ISO standards and revisions to existing standards are currently under review by U.S. Technical Advisory Groups (TAGs).

At the time of the preparation of this chapter, the referenced codes and other standards were valid. As the codes or other standards referred to here are cited without a date of publication, it is understood that the latest edition of the document applies. As these documents undergo frequent revision, the reader is encouraged to consult the most recent edition.

TYPES OF REGULATORY DOCUMENTS

The American Welding Society (AWS) uses the general term *standards* to refer to documents that govern and guide welding activities. Standards describe the technical requirements for a material, process, product, system, or service. They also provide information on the procedures, methods, equipment, and tests that are used to determine that the requirements have been met. Thus, standards comprise codes, specifications, recommended practices, classifications, methods, and guides. These documents have many similarities; however, due to their subtle differences, they are not interchangeable.

Codes and specifications are similar types of standards that use the word *shall* to indicate the mandatory use of certain materials and actions. Codes differ from specifications in that their use is generally applicable to processes. Specifications generally provide requirements for products. Codes and specifications become mandatory when so specified by one or more governmental jurisdictions or when they are referenced by contractual or other procurement documents.

Three of the most commonly recognized forms of regulatory documents are codes, standards, and specifications. Codes and other standards contain minimum engineering and regulating information pertinent to an industry or operation. They specify the welding conditions that must be addressed in welding procedures as well as those that must be demonstrated by testing to verify that a welding procedure is adequate for its intended purpose. These welding conditions, commonly referred to as *welding variables,* include conditions such as the welding process, filler metal, preheat temperature, and postweld heat treatment, among others.

An example of one such code is the American Welding Society's *Structural Welding Code—Steel,* AWS D1.1, which provides the essential variables for developing welding procedure specifications (WPSs). A welding procedure specification addresses the welding procedure and process for a particular job or operation. Many organizations and business entities use codes and other standards to develop specific in-house specifications for their particular operations.

STANDARDS-DEVELOPING ORGANIZATIONS AND WELDING-RELATED PUBLICATIONS

The organizations responsible for developing and issuing welding-related standards are listed and described in this section in alphabetical order. Some organizations publish standards spanning many categories, while others may publish in just one topic area. Table 16.1 lists these organizations and the categories they serve.

A listing of the publications and documents issued by these organizations is also included in the chapter. These lists are by no means exhaustive given the extensive contribution made by these organizations to the industry. The authors feel that the reader is best served by a listing of the most prominent publications by each organization along with contact information to facilitate

Table 16.1
Product Areas Covered by the Standards Issued by Various Organizations*

Product	AAR	AASHTO	ABS	AISC	API	AREMA	ASME	NBBPVI	ASTM	AWS	AWWA	FED	PFI	SAE	UL
Base metals		x	x		x	x	x		x	x	x	x		x	x
Bridges		x		x						x		x			
Buildings				x		x				x					
Construction equipment										x		x		x	
Cranes, hoists							x			x					
Elevators, escalators							x								
Filler metals			x				x			x		x		x	
Food, drug equipment							x								
Machine tools										x					
Military equipment												x			
Power-generation equipment			x				x	x				x			
Piping			x		x	x	x			x	x	x	x		
Presses										x					
Pressure vessels, boilers			x		x		x	x							
Railway equipment	x					x				x					
Sheet metal fabrication										x					
Ships			x							x		x			
Storage tanks					x					x	x				x
Structures, general				x		x				x					
Vehicles										x		x		x	

* AAR = Association of American Railroads; AASHTO = American Association of State Highway and Transportation Officials; ABS = American Bureau of Shipping; AISC = American Institute of Steel Construction; API = American Petroleum Institute; AREMA = American Railway Engineering and Maintenance-of-Way Association; ASME = American Society of Mechanical Engineers; NBBPVI = National Board of Boiler and Pressure Vessel Inspectors/Uniform Boiler and Pressure Vessel Laws Society; ASTM = American Society for Testing and Materials; AWWA = American Water Works Association; FED = U.S. government standards; PFI = Pipe Fabricators Institute; SAE = Society of Automotive Engineers; UL = Underwriters Laboratories.

document identification and acquisition. Dates of publications are not provided for these documents; thus, the reader is to assume that the most recent revision is referred to in each case.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO)

With its headquarters in Washington, D.C., the American Association of State Highway and Transportation Officials (AASHTO) is dedicated to the continuing development of a balanced transportation system. AASHTO's interests include aviation, highways and bridges, and public transportation as well as rail and water transportation.

The association is made up of committees, which, in turn, are comprised of member agency employees. Member agencies include the United States Department of Transportation and the Department of Transportation and Highways of the United States, Washington, D.C., and Puerto Rico. The documents developed by these committees establish rules and standards concerning the design, construction, and maintenance of highways and other transportation infrastructure.

Further information about AASHTO is available from:

American Association of State Highway and
Transportation Officials (AASHTO)
444 North Capitol Street, NW, Suite 249
Washington, DC 20001
Telephone: (202) 624-5800
Web site: www.aashto.org

Publications

The specification *Bridge Welding Code,* ANSI/AASHTO/AWS D1.5, contains the requirements for the welding of structural steel highway bridges. The 1996 edition, which includes the interim update BWC-3-REV-1, supersedes the 1995 edition, although the *Commentary* included in the 1988 edition is still applicable.

The commentary included in the 1991 edition explains the background and proper use of the provisions in the bridge welding code and includes discussions on welding metallurgy, fabrication, and erection by welding and fracture avoidance.

ASSOCIATION OF AMERICAN RAILROADS (AAR)

The Association of American Railroads (AAR) represents the major freight railroads and *Amtrak* in North America. The association endeavors to make the rail industry safe, efficient, and productive through research, development, and support programs. The collective information gathered from these ventures is exchanged among railroads, railroad customers and suppliers, and public policy interests.

Additional information about the Association of American Railroads is available from:

Association of American Railroads (AAR)
50 F Street, NW
Washington, DC 20001-1564
Telephone: (202) 639-2100
Web site: www.aar.org

Publications

The Association of American Railroads publishes the *Manual of Standards and Recommended Practices,* which is prepared by the Mechanical Division. This document provides welding information relating to railway equipment and construction and makes frequent reference to the American National Standard *Structural Welding Code—Steel,* AWS D1.1, particularly with regard to welding procedure and performance qualification. The information pertaining directly to welding is published in the following sections of Volume 1:

Section C, Part II—*Design Fabrication and Construction of Freight Cars;*
Section C, Part III—*Specifications for Freight Cars;* and
Section D—*Trucks and Truck Details.*

AMERICAN BUREAU OF SHIPPING (ABS)

The primary purpose of the American Bureau of shipping (ABS) is to control the quality and construction of ships and other marine structures. Before a ship can obtain registration and insurance in the United States, it must be "classed" (approved) by inspections and surveyor reviews. Reviews are conducted on proposed designs during construction and upon completion for compliance with ABS rules. The ship is then assigned a registration number, which also designates the vessel's class.

Further information about this organization is available from:

ABS Group, Inc.
ABS Plaza
16855 Northchase Drive
Houston, TX USA 77060-6008
Telephone: (281) 877-6100
Web site: www.eagle.org

Publications

The American Bureau of Shipping publishes standards that cover a wide range of construction technologies, including welding. Among the organization's welding related publications is *ABS Rule Requirements for Materials and Welding,* Part 2. This publication addresses welding in Section 1, *Materials for Hull Construction and Equipment;* Section 2, *Materials for Machinery, Boilers, Pressure Vessels and Piping;* and Section 3, *Welding and Fabrication,* particularly Part A, *Hull Construction*; Part B, *Boilers, Unfired Pressure Vessels, Piping, and Engineering Structures;* and Part C, *Weld Test.*

With respect to consumables, inspection, marine applications, and piping, the American Bureau of Shipping publishes *Approved Welding Consumables,* ABS 27; *Rules for Nondestructive Inspection of Hull Welds,* ABS 14; *Rules for Building and Classing Aluminum Vessels*, ABS 3; and *Pipelines—Gas and Liquid Petroleum—Part 2: Welding*, respectively.

AMERICAN INSTITUTE OF STEEL CONSTRUCTION (AISC)

The American Institute of Steel Construction (AISC) represents and serves the structural steel industry in the United States. AISC helps promote the fabrication and application of structural steel through research and development, education, technical assistance, standardization, and quality control. AISC references the American Welding Society's *Structural Welding Code—Steel,* AWS D1.1, for welding procedure and weld performance qualifications.

More information about the American Institute of Steel Construction is available from:

American Institute of Steel Construction (AISC)
One East Wacker Drive, Suite 3100
Chicago, IL 60601-2001
Telephone: (312) 670-2400
Web site: www.aisc.org

Publications

The American Institute of Steel Construction publishes many reference materials that are of interest to engineers, architects, fabricators, contractors, building officials, and others associated with the structural steel industry. Among these, the publication *Structural Members, Specifications, and Codes,* Volume I of *the Load Resistance Factor Design (LRFD) Manual*, contains seven parts:

1. *Dimensions and Properties,*
2. *Essentials of Load Resistance Factor Design,*
3. *Column Design,*
4. *Beam and Girder Design,*
5. *Composite Design,*
6. *Specifications and Codes,* and
7. *Miscellaneous Data and Mathematical Tables.*

Volume I also incorporates the following AISC publications:

Code of Standard Practice for Steel Buildings and Bridges, S303;
LRFD Specification Supplement No. 1, S347;
LRFD Specification for Structural Steel Buildings (and Commentary), S342;
Seismic Provisions for Structural Steel Buildings, S341; and
Specification for Single-Angle Members, S343.

Volume II of the *Load Resistance Factor Design (LRFD) Manual, Connections,* contains six parts, which are numbered beginning with Part 8, as follows:

8. *Bolts, Welds, and Connected Elements;*
9. *Simple Shear and Partially Restrained (PR) Moment Connections;*
10. *Partially Restrained (PR) Moment Connections;*
11. *Connections for Tension and Compression;*
12. *Other Connections;* and
13. *Construction Industry Organizations.*

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

The American National Standards Institute (ANSI) has been administrator and coordinator of the U.S. private-sector voluntary standardization system for 80 years. ANSI promotes the use of U.S. standards internationally, advocates U.S. policy and technical positions in international and regional standards organizations, and encourages the adoption of international standards as national standards when these meet the needs of the user community.

The American National Standards Institute's primary goal is the enhancement of global competitiveness of U.S. business by promoting voluntary consensus standards. The Institute represents the interests of its nearly 1400 corporate, organizational, governmental, institutional, and international members.

U.S. National Standards

The American National Standards Institute does not itself develop American National Standards (ANSs); rather, it facilitates their development by establishing consensus among 175 qualified groups. ANSI-accredited developers are committed to supporting the development of national and, in many cases, international standards, addressing the critical trends of technological innovation, marketplace globalization, and regulatory reform. These groups include standards bodies dedicated to welding (such as the American Welding Society) and those who have some interest in welding.

ANSI functions as an administrator, ensuring that due process is followed in reaching a consensus. The organization reviews the steps in the development process before approving a document as an ANSI standard. In 1999 alone, the number of American National Standards increased by nearly 5.5% to a new total of 14,650 approved standards.

International Standards

ANSI is the sole U.S. representative and dues-paying member of the two major nontreaty international standards organizations—the International Organization for Standardization (ISO) and, through the U.S. National Committee (USNC), the International Electrotechnical Commission (IEC). ANSI was a founding member of the ISO and plays an active role in its governance. ANSI is one of five permanent members to the governing ISO Council and one of four permanent members of ISO's Technical Management Board.

Through ANSI, the United States has immediate access to the ISO and IEC standards-development processes. ANSI not only participates predominantly in technical programs conducted by ISO (78% of all ISO technical committees) and the IEC (91% of all IEC technical committees), but it also administers many key committees and subgroups (16% and 17% in ISO and the IEC, respectively).

As part of its responsibilities as the U.S. member body to ISO and the IEC, ANSI accredits U.S. Technical Advisory Groups (U.S. TAGs) or USNC Technical Advisors (TAs). The primary purpose of the U.S. TAGs and TAs is to develop and transmit, through ANSI, the United States' positions to the international technical committees.

In many instances, U.S. standards are taken forward, through ANSI or its USNC, to ISO or the IEC, where they are adopted in whole or in part as international standards. Since the work of the international technical committees is carried out by volunteers from industry and government, not ANSI staff, the success of these efforts often depends upon the willingness of U.S. industry and the U.S. government to commit the resources required to ensure strong U.S. technical participation in international standards.

More information about the American National Standards Institute is available from:

American National Standards Institute (ANSI)
1819 L Street, NW 6th Floor
Washington, DC 20036
Telephone: (202) 293-8020
Web site: http://www.ansi.org

AMERICAN PETROLEUM INSTITUTE (API)

The American Petroleum Institute is a major national trade association that acts on behalf of the petroleum industry. Headquartered in Washington, D.C., API was founded in 1919 to provide for the standardization of engineering specifications concerning drilling and production equipment. API's members ascertain the petroleum industry's positions and the standards that govern its day-to-day operations around the globe.

Further information about this organization can be obtained from:

The American Petroleum Institute (API)
1220 L Street, NW
Washington, DC 20005
Telephone: (202) 682-8000
Web site: www.api.org

Publications

Welding-related specifications issued by the American Petroleum Institute include:

Design and Construction of Large, Welded, Low-Pressure Storage Tanks, API Std 620;
Field Welded Tanks for Storage of Production Liquids, ANSI/API Spec 12D;
Inspection of Atmospheric and Low Pressure Storage Tanks, RP575;
Inspection of Pressure Vehicles, RP 572;
Procedures for Welding or Hot Tapping on Equipment in Service, Publ 2201;
Shop Welded Tanks for Storage of Production Liquids, ANSI/API Spec 12F;
Tank Inspection, Repair, Alteration, and Reconstruction, API Std 653, 653-A3;
Welded Tanks for Oil Storage, API Std 650, 650-A1;
Welding Connections to Pipe, RP5C6; and
Welding of Pipelines and Related Facilities, ANSI/API 1104.

AMERICAN RAILWAY ENGINEERING AND MAINTENANCE-OF-WAY ASSOCIATION (AREMA)

The American Railway Engineering and Maintenance-of-Way Association (AREMA) was formed on October 1, 1997 as an alliance of the American Railway Bridge and Building Association, the American Railway Engineering Association, and the Roadmasters and

Maintenance-of-Way Association, along with the functions of the communications and Signal Division of the Association of American Railroads. AREMA's purpose is the advancement of technical and practical knowledge and recommended practices related to the design, construction, and maintenance of railway infrastructure.

More information about AREMA is available from:

AREMA Headquarters
8201 Corporate Drive, Suite 1125
Landover, MD 20785-2230
Telephone: (301) 459-3200
Web site: www.arema.org

Publications

The American Railway Engineering and Maintenance of Way Association publishes the following welding-related publications:

Manual for Railway Engineering,
Manual of Recommended Practices—Signals,
Manual of Recommended Practices—Communications, and
Field Handbook for Concrete Railway Structures.

AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME) INTERNATIONAL

The American Society of Mechanical Engineers (ASME International), founded in 1880, is responsible for more than 600 technical standards, including the *Boiler and Pressure Vessel Code* and the *Code for Pressure Piping*. ASME International has extended its programs for codes, standards, accreditation, and certification to include the registration (certification) of quality systems in conformance with standards set by the International Organization for Standardization (ISO), including ISO 9000.

Additional information about ASME International can be obtained from:

ASME International
Three Park Avenue
New York, NY 10016-5990
Telephones: 800-THE-ASME (United States/Canada)
95-800-843-2763 (Mexico)
973-882-1167 (outside North America)
Web site: www.asme.org

Publications

Two standing committees are actively involved in the formulation, revision, and interpretation of standards relating to products that are fabricated by welding. These committees are responsible for preparing the ASME *Boiler and Pressure Vessel Code* and the *Code for Pressure Piping,* which are American National Standards.

ASME *Boiler and Pressure Vessel Code.* The *Boiler and Pressure Vessel Code* is comprised of eleven sections. Sections I, III, IV, VIII, and X address the design, construction, and inspection of boilers and pressure vessels, while Sections VI, VII, and XI focus on the care and operation of boilers and nuclear power plant components. Sections II, V, and IX discuss qualifications for material specifications, nondestructive examination, and welding and brazing, respectively. These sections are listed below:

Section I, *Power Boilers;*
Section II, *Materials;*
Section III, *Rules for Construction of Nuclear Power Plant Components;*
Section IV, *Rules for Construction of Heating Boilers;*
Section V, *Nondestructive Examination;*
Section VI, *Recommended Rules for Care and Operation of Heating Boilers;*
Section VII, *Recommended Guidelines for the Care of Power Boilers;*
Section VIII, *Rules for Construction of Pressure Vessels;*
Section IX, *Welding and Brazing Qualifications;*
Section X, *Fiber-Reinforced Plastic Pressure Vessels;* and
Section XI, *Rules for In-Service Inspection of Nuclear Power Plant Components*.

The ASME *Boiler and Pressure Vessel Code* is referenced in the safety regulations of most states and major cities of the United States as well as the provinces of Canada. A number of federal agencies include the code as part of their respective regulations. This code is also recommended as a standard for construction by the Uniform Boiler and Pressure Vessel Laws Society (UBPVLS), which has as its objective the uniformity of laws, rules, and regulations that affect boiler and pressure vessel fabricators, inspection agencies, and users. This same organization recommends the *National Board Inspection Code*, NB-23, issued by the National Board of Boiler and Pressure Vessel Inspectors (NBBPVI), discussed below, as the standard for inspection and repair.

The ASME *Boiler and Pressure Vessel Code* is unique in that it requires a third-party inspection independent of the fabricator and the user. The NBBPVI facilitates the third-party inspection of ASME work by training, examining, and commissioning individuals to perform inspections and examinations of components built to the ASME *Boiler and Pressure Vessel Code*.

These inspectors are employed by authorized inspection agencies (usually insurance companies) or by jurisdictional authorities. Possession of an ASME Certificate of Authorization (also known as a *Code Stamp*) is necessary prior to the manufacture of components according to the ASME *Boiler and Pressure Vessel Code.*

This code also specifies that prior to building a boiler or pressure vessel, the fabricator must have a quality control system and a manual that describes it. The system must be acceptable to the authorized inspection agency and either the jurisdictional authority or the NBBPVI. Based on the results of an audit of the fabricator's quality system, ASME may issue the fabricator a Certificate of Authorization and a code symbol stamp. The authorized inspection agency is also involved in monitoring the fabrication and field erection of boilers and pressure vessels. An authorized inspector must be satisfied that all applicable provisions of the code have been followed before allowing the fabricator to apply its code symbol stamp to the name plate attached to the vessel.

Code for Pressure Piping. The ASME *Code for Pressure Piping,* B31, consists of seven sections. The sections specify the minimum requirements for the design, materials, fabrication, testing, and inspection of a particular type of piping system. These seven sections are listed below:

- *Power Piping,* B31.1;
- *Process Piping,* B31.3;
- *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids,* B31.4;
- *Refrigeration Piping,* B31.5;
- *Gas Transmission and Distribution Piping Systems,* B31.8;
- *Building Services Piping,* B31.9; and
- *Slurry Transportation Piping Systems,* B31.11.

All sections of the ASME *Code for Pressure Piping* require the performance qualification of the welders and welding operators and the qualification of the welding procedures to be used in construction. Some sections require these qualifications to be performed in accordance with *Welding and Brazing Qualifications,* Section IX of the *Boiler and Pressure Vessel Code*. The American Petroleum Institute's *Welding of Pipelines and Related Facilities,* ANSI/API 1104, is permitted in some sections as an alternative to Section IX.

AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING (ASNT)

The American Society for Nondestructive Testing (ASNT), comprised of approximately 75 local and 12 international sections (chapters), was founded in 1941. From its world headquarters in Columbus, Ohio, ASNT serves as a major international source for nondestructive testing Level III certification by examination by professionals holding valid ASNT Level III certificates. ASNT also offers the Industrial Radiography Radiation Safety Personnel (IRRSP) certification program, instituted in cooperation with the United States Nuclear Regulatory Commission, which provides a third-party national safety program for industrial radiographers. In November 1996, examinations began for the ASNT Central Certification Program (ACCP), a new, independent, portable nondestructive testing certification by examination.

The Society also operates the ASNT Information Center, which provides a central archive and retrieval point for information related to nondestructive testing. Literature searches and document delivery are among the Information Center's key services.

More information about ASNT is available from:

American Society for Nondestructive Testing (ASNT)
1711 Arlington Lane
P.O. Box 28518
Columbus, OH 43228-0518
Telephones: (614) 274-6003; (800) 222-2768
Web site: http://www.asnt.org

Publications

The American Society for Nondestructive Testing maintains a large catalog of nondestructive testing education and reference materials, providing information on virtually every aspect of nondestructive testing. Publications produced by the Society include *Materials Evaluation,* the Society's monthly technical journal; *Research in Nondestructive Evaluation,* a quarterly journal publishing original research in all areas of nondestructive examination; and the *Nondestructive Testing Handbook*, recognized as a definitive nondestructive testing reference source.

The American Society for Nondestructive Testing plays a major role in the certification and qualification of nondestructive examination personnel by developing and maintaining *Recommended Practice No. SNT-TC-1A* and *Standard for Qualification and Certification of Nondestructive Testing Personnel,* ANSI/ASNT CP-189. ASNT also publishes Level III study guides and other educational materials.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

The American Society for Testing and Materials (ASTM) is a not-for-profit organization that provides a forum for producers, users, consumers, and others to write standards for materials, products, systems, and services. Organized in 1898, ASTM is one of the largest voluntary standards development systems in the world. Technical research and testing is carried out voluntarily by over 100 committees and approximately 35,000 technically qualified ASTM members located throughout the world.

ASTM technical committees are the specific forums in which ASTM standards are developed. The 132 main technical committees are each divided into subcommittees. The subcommittees are further subdivided into task groups. Task group members need not be ASTM members; in fact, many task groups seek non-ASTM members to provide special expertise in a given area.

Based on the work of these standards-writing committees, ASTM publishes consensus standards for test methods, specifications, practices, guides, classifications, and terminology. While no committee focuses solely on welding, welding-related issues are addressed by various technical committees. For example, welding inspection is covered by ASTM Committee E07. Welding consumables are covered by American Welding Society specifications.

ASTM publishes the *Annual Book of ASTM Standards,* which incorporates new and revised standards. This publication is divided into 15 sections, which in turn comprise 73 volumes and an index. Specifications for the metal products, test methods, and analytical procedures of interest to the welding industry are found in the first three sections. Section 1 provides information about iron and steel products. Section 2 addresses nonferrous metal products, and Section 3 discusses metal test methods and analytical procedures.

Prefix letters, which are part of each specification's alphanumeric designation, provide a general idea of the document's content. These prefixes include "A" for ferrous metals, "B" for nonferrous metals, and "E" for miscellaneous subjects, including examination and testing. When ASME adopts ASTM specifications for use in construction according to the *Boiler and Pressure Vessel Code*, and these versions are presented in Section II of said code. When this occurs, ASME adds an "S" in front of the ASTM designation (e.g., ASTM A-36 becomes ASME SA-36).

The largest group of welded products covered by ASTM specifications is that comprised of steel pipe and tubing. Only when pipe is arc welded does ASTM require that procedures and welders be qualified to Section IX of the ASME *Boiler and Pressure Vessel Code.* Most pipe made in adherence to ASTM specifications is produced using electric resistance welding or furnace butt welding; neither method is covered by Section IX.

More information on ASTM is available from:

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959
Telephone: (610) 832-9585
Web site: www.astm.org

Publications

The American Society for Testing and Materials publishes approximately 130 welding-related codes and standards. A partial listing is presented below:

Acoustic Emission Monitoring during Continuous Welding, Standard Practice for, ASTM E749;

Acoustic Emission Monitoring during Resistance Spot-Welding, Standard Practice for, ASTM E751;

Determining the Short Term Tensile Weld Strength of Chemical-Resistant Thermoplastics, Standard Practice for, ASTM C1147-95;

Electromagnetic (Eddy-Current) Examination of Seamless and Welded Tubular Products, Austenitic Stainless Steel and Similar Alloys, Standard Practice for, ASTM E426;

Electromagnetic (Eddy-Current) Examination of Type F Continuously Welded (CW) Ferromagnetic Pipe and Tubing Above the Curie Temperature, Standard Practice for, ASTM E1033;

Standard Reference Radiographs for Examination of Aluminum Welds, ASTM E1648;

Standard Reference Radiographs for Examination of Steel Fusion Welds, ASTM E390;

Standard Specification for Austenitic Chromium-Nickel-Silicon Alloy Steel Seamless and Welded Tubing, ASTM A953;

Ultrasonic Contact Examination of Weldments, Standard Practice for, ASTM E164;

Ultrasonic C-Scan Bond Evaluation of Brazed or Welded Electrical Contact Assemblies, *Standard Guide for,* ASTM B773; and

Ultrasonic Examination of Longitudinal Welded Pipe and Tubing, *Standard Practice for,* ASTM E273.

AMERICAN SOCIETY FOR QUALITY (ASQ)

As the secretariat for the American National Standards Institute's (ANSI) ASC Z-1 Committee on Quality Assurance, the American Society for Quality (ASQ) provides direction on and builds consensus for national and international standards. ASQ volunteers play key roles in developing the ISO 9000 series standards, originally adopted nationally as the Q90 series standards and recently revised and redesignated as the Q9000 series standards. They do so through their involvement in the U.S. Technical Advisory Group for ISO Technical

Committee 176, administered by ASQ on behalf of ANSI.

The ISO 9000 standards pertain to quality management systems. ISO 14,000 standards pertain to environmental management systems. It should be noted that these standards concern management systems, not products. The three major auto makers in the United States have developed the QS-9000 requirements based on the ISO 9000 standards.

More information on the American Society for Quality is available from:

American Society for Quality
P.O. Box 3066
Milwaukee, WI 53201-3066
Telephone: 800-248-1946
Web site: www.asq.org

AMERICAN WATER WORKS ASSOCIATION (AWWA)

In 1931, three subcommittee members from the American Water Works Association (AWWA) prepared the publication *Standard Specifications for Riveted Steel Elevated Tanks and Standpipes*. These specifications were later published in a 1935 edition of *Journal AWWA*. In 1940, in cooperation with the American Welding Society, this standard was expanded to include welded construction.

Further information about the American Water Works Association is available from:

American Water Works Association (AWWA)
6666 W. Quincy Avenue
Denver, CO 80235
Telephone: (303) 794-7711
Web site: www.awwa.org

Publications

The American Water Works Association (AWWA) publishes two standards pertaining to the welding of water storage and transmission systems. These are *Field Welding of Steel Water Pipe,* ANSI/AWWA C206, and *Welded Steel Tanks for Water Storage,* ANSI/AWWA D100.

AMERICAN WELDING SOCIETY (AWS)

Since 1919, the mission of the American Welding Society (AWS) has been to provide quality service to the welding industry and advance the science, technology, and application of materials joining. The work of more than 25 standing committees and nearly 100 technical committees serves as the cornerstone for the organization's publishing initiatives.

Additional information about the American Welding Society is available from:

American Welding Society (AWS)
550 N.W. LeJeune Road
Miami, FL 33126-5699
Telephone: (800) 443-9353
Web site: www.aws.org

Publications

At its headquarters in Miami, Florida, the American Welding Society publishes over 175 documents covering the use and quality control of welding. These documents include codes, specifications, recommended practices, classifications, methods, and guides.

All standards published by the American Welding Society are voluntary consensus standards that have been developed in accordance with the guidelines of the American National Standards Institute (ANSI). They are reviewed every five years, at which time they are reapproved, revised, or withdrawn.

Publication areas include the following:

1. Reference;
2. Definitions and symbols;
3. Welding, brazing, and cutting processes;
4. Construction and manufacturing;
5. Filler metals;
6. Qualification and certification;
7. Inspection and testing; and
8. Safety and health.

In addition, the American Welding Society publishes welding-related materials in the areas of metallurgy, education and training, welding procedure specifications, and computerized welding information. A partial listing of the publications in the major topic areas is presented below.

Reference. The American Welding Society publishes a number of valuable reference sources on all facets of welding and allied processes. A listing of these publications can be obtained by contacting the American Welding Society.

Definitions and Symbols. The publication *Standard Welding Terms and Definitions,* AWS A3.0, lists and defines the standard terms that are used to convey information about welding, brazing, soldering, thermal spraying, and thermal cutting. Nonstandard terms are defined by reference to the standard terms. A glossary of terms and definitions from this publication appears in Appendix A of this volume.

The publication *Standard Symbols for Welding, Brazing, and Nondestructive Examination,* ANSI/AWS A2.4, describes the standard symbols that are used to convey welding, brazing, and nondestructive testing requirements on drawings. The symbols presented in this publication are intended to facilitate communication between designers and fabrication personnel.

Welding, Brazing, Cutting, and Surfacing Processes. AWS publishes recommended practices and guides for arc and oxyfuel welding and cutting, brazing, resistance welding, and thermal spraying. The following is a partial list of documents organized according to process:

ARC AND GAS WELDING AND CUTTING

Air Carbon Arc Gouging and Cutting, Recommended Practices for, ANSI/AWS C5.3;
Electroslag and Electrogas Welding, Recommended Practices for, AWS C5.7;
Gas Metal Arc Welding, Recommended Practices for, AWS C5.6;
Gas Tungsten Arc Welding, Recommended Practices for, AWS C5.5;
Oxyfuel Gas Cutting, Operator's Manual for, AWS C4.2;
Plasma Arc Cutting, Recommended Practices for, AWS C5.2;
Plasma Arc Welding, Recommended Practices for, AWS C5.1;
Shielding Gases for Welding and Plasma Arc Cutting, Recommended Practices for, AWS C5.10; and
Stud Welding, Recommended Practices for, ANSI/AWS C5.4.

BRAZING

Aluminum Brazing, Specification for, AWS C3.7;
Design, Manufacture, and Inspection of Critical Brazed Components, Recommended Practices for, AWS C3.3;
Filler Metals for Braze Welding, Specification for, AWS A5.8;
Fluxes for Brazing and Braze Welding, Specification for, AWS A5.31;
Furnace Brazing, Specification for, AWS C3.6;
Induction Brazing, Specification for, AWS C3.5;
Torch Brazing, Specification for, AWS C3.4; and
Ultrasonic Inspection of Brazed Joints, Recommended Practices for, AWS C3.8.

RESISTANCE WELDING

Resistance Welding, Recommended Practices for, AWS C1.1, and
Resistance Welding of Carbon and Low Alloy Steels, Specification for, C1.4M/C1.4.

SURFACING PROCESSES

Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Composites, Guide for the, AWS C2.18;
Thermal Spray Manual, TSM; and
Thermal Spraying: Practice, Theory, and Application, TSS.

Construction and Manufacturing. AWS publishes standards that provide regulations for various welding applications in the construction and manufacturing industries. These include automotive, machinery and equipment, marine, piping and tubing, and structural applications, among others. Key documents published in these areas are listed below:

AUTOMOTIVE APPLICATIONS

Automotive and Light Truck Weld Quality—Arc Welding, Specification for, AWS D8.8;
Automotive Resistance Spot Welding Electrodes, Standard for, AWS D8.6; and
Automotive Weld Quality—Resistance Spot Welding, Recommended Practices for, AWS D8.7; and
Test Methods for Evaluating the Resistance Spot Welding Behavior of Automotive Sheet Steel Material, Recommended Practices for, AWS D8.9.

MACHINERY AND EQUIPMENT

Metal Cutting Machine Tool Weldments, Specification for, ANSI/AWS D14.2;
Railroad Welding Specification—Cars and Locomotives, ANSI/AWS D15.1;
Rails and Related Rail Components for Use by Rail Vehicles, Recommended Practices for the Welding of, AWS D15.2;
Welded Joints in Machinery and Equipment, Specification for, AWS D14.4;
Welding Earthmoving and Construction Equipment, Specification for, AWS D14.3;
Welding Industrial and Mill Cranes and Other Material Handling Equipment, Specification for, ANSI/AWS D14.1;
Welding of Presses and Press Components, Specification for, AWS D14.5; and
Welding of Rotating Elements of Equipment, Specification for, AWS D14.6.

MARINE APPLICATIONS

Aluminum Hull Welding, Guide for, ANSI/AWS D3.7;
Steel Hull Welding, Guide for, ANSI/AWS D3.5; and
Underwater Welding, Specification for, ANSI/AWS D3.6.

PIPING AND TUBING

Aluminum and Aluminum Alloy Pipe, Recommended Practices for Gas Shielded Arc Welding of, ANSI/AWS D10.7;
Austenitic Chromium-Nickel Stainless Steel Piping and Tubing, Recommended Practices for Welding, ANSI/AWS D10.4;
Brazing of Copper Pipe and Tubing for Medical Gas Systems, Recommended Practices, AWS D10.13;
Chromium-Molybdenum Steel Piping and Tubing, Recommended Practices for Welding of, ANSI/AWS D10.8;
Gas Tungsten Arc Welding of Titanium Piping and Tubing, Recommended Practices for, ANSI/AWS D10.6;
Local Heat Treatment of Welds in Piping and Tubing, AWS D10.10;
Low Carbon Steel Pipe, Recommended Practices and Procedures for Welding, AWS D10.12; and
Root Pass Welding of Pipe without Backing, Recommended Practices for, ANSI/AWS D10.11.

STRUCTURAL APPLICATIONS

Bridge Welding Code (SI units), AWS D1.5;
Bridge Welding Code (U.S. customary units), AWS D1.5;
Structural Welding Code—Aluminum, ANSI/AWS D1.2;
Structural Welding Code—Reinforcing Steel, ANSI/AWS D1.4;
Structural Welding Code—Sheet Steel, ANSI/AWS D1.3;
Structural Welding Code—Stainless Steel, D1.6; and
Structural Welding Code—Steel, ANSI/AWS D1.1.

Filler Metals. The American Welding Society's filler metal specifications address the use of most types of consumables that are used in conjunction with the various welding and brazing processes. These specifications comprise both mandatory and nonmandatory provisions. The mandatory provisions address topics such as chemical and mechanical properties, manufacturing, testing, and packaging. The nonmandatory provisions, which are presented in an appendix, are provided as a source of information on the classification, description, and intended use of the filler metals listed in the publication.

Following is a listing of AWS filler metal specifications:

Aluminum and Aluminum Alloy Electrodes for Shielded Metal Arc Welding, Specification for, ANSI/AWS A5.3/A5.3M;
Bare Aluminum and Aluminum Alloy Welding Rods and Electrodes, Specification for, ANSI/AWS A5.10;
Carbon and Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding, Specification for, ANSI/AWS A5.25/A5.25M;
Carbon and Low Alloy Steel Electrodes for Electrogas Welding, Specification for, ANSI/AWS A5.26/A5.26M;
Carbon and Low Alloy Steel Welding Rods for Oxyfuel Gas Welding, Specification for, ANSI/AWS A5.2;
Carbon Steel Electrodes and Fluxes for Submerged Arc Welding, Specification for, ANSI/AWS A5.17/A5.17M;
Carbon Steel Electrodes for Flux Cored Arc Welding, Specification for, ANSI/AWS A5.20;
Carbon Steel Electrodes for Shielded Metal Arc Welding, Specification for, ANSI/AWS A5.1;
Carbon Steel Filler Metals for Gas Shielded Arc Welding, Specification for, ANSI/AWS A5.18;
Composite Surfacing Welding Rods and Electrodes, Specification for, ANSI/AWS A5.21;
Consumable Inserts, Specification for, ANSI/AWS A5.30;
Copper and Copper Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.7;
Bare Stainless Steel Welding Electrodes and Rods, Specification for, ANSI/AWS A5.9;
Covered Copper and Copper Alloy Arc Welding Electrodes, Specification for, ANSI/AWS A5.6;
Stainless Steel Electrodes for Shielded Metal Arc Welding, Specification for, ANSI/AWS A5.4;
Filler Metals for Brazing and Braze Welding, Specification for, ANSI/AWS A5.8;
Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding, Specification for, ANSI/AWS A5.23/A5.23M;
Low Alloy Steel Electrodes for Flux Cored Arc Welding, Specification for, ANSI/AWS A5.29;
Low Alloy Steel Electrodes for Shielded Metal Arc Welding, Specification for, ANSI/AWS A5.5;
Low Alloy Steel Filler Metals for Gas Shielded Arc Welding, Specification for, ANSI/AWS A5.28;
Magnesium Alloy Welding Rods Electrodes and Rods, Specification for, ANSI/AWS A5.19;
Nickel and Nickel Alloy Bare Welding Rods and Electrodes, Specification for, ANSI/AWS A5.14/A.14M;

Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding, Specification for, ANSI/AWS A5.11/A5.11M;
Solid Surfacing Welding Rods and Electrodes, Specification for, ANSI/AWS A5.13;
Stainless Steel Electrodes for Flux Cored Arc Welding and Stainless Steel Flux Cored Rods for Gas Tungsten Arc Welding, Specification for, ANSI/AWS A5.22;
Titanium and Titanium Alloy Welding Rods and Electrodes, Specification for, ANSI/AWS A5.16;
Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting, Specification for, ANSI/AWS A5.12/A5.12M;
Welding Electrodes and Rods for Cast Iron, Specification for, ANSI/AWS A5.15; and
Zirconium and Zirconium Alloy Welding Rods and Electrodes, Specification for, ANSI/AWS A5.24.

Most AWS filler metal specifications have been approved by ANSI as American National Standards and adopted by the United States Department of Defense and ASME. When ASME adopts an AWS filler metal specification in its entirety or with revisions, the letters "SF" are added to the AWS alphanumeric designation. Thus, the document having specification "ASME SFA-5.4" would be similar if not identical to the document published as "AWS A5.4."

The American Welding Society also publishes documents to aid users with the purchase of filler metals. These include the following:

Filler Metal Procurement Guidelines, AWS A5.01;
Filler Metal Comparison Charts, FMC;
User's Guide to Filler Metals, AWS UGFM; and
International Filler Metal Classification, AWS IFS.

Qualification and Certification. The following AWS publications provide standards for welding procedure and performance qualification:

Guide for Thermal Spray Operator Qualification, ANSI/AWS C2.16;
Standard for Brazing Procedure and Performance Qualification, AWS B2.2
Standard for Welding Procedure and Performance Qualification, ANSI/AWS B2.1; and
Standard Method for Evaluating the Strength of Brazed Joints in Shear, ANSI/AWS C3.2.

Inspection and Testing. Although many of the AWS codes address inspection and testing concerns, the following apply entirely to the testing and inspection of welds:

Guide for the Nondestructive Inspection of Welds, ANSI/AWS B1.10; and
Standard Methods for Mechanical Testing of Welds, ANSI/AWS B4.0.

Safety and Health. The American Welding Society has developed standards addressing welding safety and health issues as they apply to particular uses and processes. These publications, listed below, should be used in conjunction with other applicable governmental or private safety directives:

Electron Beam Welding and Cutting, Recommended Safe Practices for, AWS F2.1;
Evaluating Contaminants in the Welding Environments, A Sampling Strategy Guide for, ANSI/AWS F1.3;
Lens Shade Selector, AWS F2.2;
Measuring Fume Generation Rates and Total Fume Emission for Welding and Allied Processes, Laboratory Method for, ANSI/AWS F1.2;
Preparation for Welding and Cutting of Containers and Piping, Recommended Safe Practices for the, AWS F4.1;
Safety in Welding and Cutting and Allied Practices, ANSI/AWS Z49.1;
Sampling Airborne Particulates Generated by Welding and Allied Processes, Method for, ANSI/AWS F1.1;
Sampling and Analyzing Gases for Welding and Allied Processes, Methods for, ANSI/AWS F1.5;
Sound Level Measurement of Manual Arc Welding and Cutting Processes, Method for, AWS F6.1; and
Welding Fume Control, Guide for, AWS F3.1.

CSA INTERNATIONAL

CSA International, known as the Canadian Standards Association (CSA) until 1999, is a not-for-profit organization with offices and partners in Canada, the United States, and other locations throughout the world. Established in 1919, CSA International is a leader in the field of standards development and application of these standards through product certification, management systems registration, and information products.

More information about this organization can be obtained from:

CSA International
178 Rexdale Boulevard
Etobicoke (Toronto), ON
Canada M9W 1R3
Telephone: (800) 463-6727
Web site: www.csa-international.org

Publications

Over 15,000 publications in the electrical, electronic, communications, environmental, construction, quality management systems, and health and safety fields are available from CSA International. A partial list of welding-related publications is presented below:

Carbon Steel Covered Electrodes for Shielded Metal Arc Welding, CAN/CSA-W48.1-M;
Carbon Steel Electrodes for Flux- and Metal-Cored Arc Welding, CAN/CSA-W48.5-M;
Certification of Companies for Fusion Welding of Aluminum, CAN/CSA-W47.2-M;
Certification of Companies for Fusion Welding of Steel Structures, CAN/CSA-W47.1;
Certification of Welding Inspection Organizations, CAN/CSA-W178.1;
Certification of Welding Inspectors, CAN/CSA-W178.2;
Chromium and Chromium-Nickel Steel Covered Electrodes for Shielded Metal Arc Welding, CAN/CSA-W48.2-M;
Corrugated Steel Pipe Products, CAN/CSA-G401;
Fluxes and Carbon Steel Electrodes for Submerged Arc Welding, CAN/CSA-W48.6;
General Requirements for Rolled or Welded Structural Quality Steel/Structural Quality Steel CAN/CSA-G40.20/G40.21;
Hot Dip Galvanizing of Irregularly Shaped Articles, CAN/CSA-G164-M;
Low Alloy Steel Covered Electrodes for Shielded Metal Arc Welding, CAN/CSA-W48.3;
Metric Dimensions for Structural Steel Shapes and Hollow Structural Sections, CAN/CSA-G312.3-M;
Preferred Metric Dimensions for Flat Metal Products, CAN/CSA-G312.1;
Preferred Metric Dimensions for Round, Square, Rectangular, and Hexagonal Metal Products, CAN/CSA-G312.2-M;
Resistance Welding Qualification Code for Fabricators of Structural Members Used in Buildings, CAN/CSA-W55.3;
Safety in Welding, Cutting and Allied Processes, CAN/CSA-W117.2;
Solid Carbon Steel Filler Metals for Gas Shielded Arc Welding, CAN/CSA-W48.4;
Sprayed Metal Coatings for Atmospheric Corrosion Protection, CAN/CSA-G189;
Steel-Surface Finish of Hot-Rolled Plates and Wide Flats-Delivery Requirements (Adopted ISO 7788), CAN/CSA-G40.23;
Supplement No.1, Steel Fixed Offshore Structures, to W59-1989, CAN/CSA-W59.S1;
Terminologie française du soudage, Section 1: Discontinuités et défauts de soudage, CAN/CSA-W375 SEC.1-F;
Terminologie française du soudage, Section 2: Procédés de soudage et techniques connexes, CAN/CSA-W375 SEC.2-F;
Terminologie française du soudage, Section 3: Assemblages, préparations et soudures CAN/CSA-W375 SEC.3-F;
Welded Aluminum Construction, CAN/CSA-W59.2-M;
Welded Steel Construction (Metal Arc Welding) (Imperial version), CAN/CSA-W59;
Welded Steel Construction (Metal Arc Welding) (Metric version), CAN/CSA-W59-M; and
Welding of Reinforcing Bars in Reinforced Concrete Construction, CAN/CSA-W186-M.

COMPRESSED GAS ASSOCIATION (CGA)

The Compressed Gas Association (CGA) promotes, develops, represents, and coordinates technical and standardization activities in the compressed gas industries, including the end uses of products. The CGA operates through a committee system comprised of 200 member organizations and in cooperation with governmental agencies. The association represents manufacturers, distributors, suppliers, and transporters of gases, cryogenic liquids, and related products. The CGA's sphere of influence includes industrial, medical, and specialty gases in compressed or liquefied form, and a range of gas handling equipment.

Additional information about the Compressed Gas Association can be obtained from:

Compressed Gas Association (CGA)
1725 Jefferson Davis Highway, Suite 104
Arlington, VA 22202-4102
Telephone: (703) 412-0900
Web site: www.cganet.com

Publications

The Compressed Gas Association publishes information on welding, repair, inspection, and procedure and performance qualification. Also addressed are the properties, manufacture, transportation, storage, handling, and safety procedures for gases. A partial listing of publications by topic is presented below:

WELDING-RELATED CODES AND STANDARDS

Standards for Welding on Thin-Walled Steel Cylinders, CGA C-3

GAS STANDARDS

Acetylene, CGA G-1;
Carbon Dioxide, CGA G-6;
Commodity Specification for Acetylene, CGA G-1.1;
Commodity Specification for Argon, CGA G-11.1;
Commodity Specification for Carbon Dioxide, CGA G-6.2;
Commodity Specification for Helium, CGA G-9.1;
Commodity Specification for Hydrogen, CGA G-5.3;
Commodity Specification for Nitrogen, CGA G-10.1;
Commodity Specification for Oxygen, CGA G-4.3;
Hydrogen, CGA G-5;
Oxygen, CGA G-4; and
The Inert Gases Argon, Nitrogen, and Helium, CGA P-9.

SAFETY

Accident Prevention in Oxygen-Rich and Oxygen-Deficient Atmospheres, CGA P-14;
Avoiding Hazards in Confined Work Spaces During Maintenance, Construction, and Similar Activities, CGA SB-153/4;
Handbook of Compressed Gases;
Handling Acetylene Cylinders in Fires, CGA SB-4;
Hazard Ratings for Compressed Gases, CGA P-19;
Oxygen-Deficient Atmospheres (Less than 19.5%), CGA SB-2;
The Responsible Management and Disposition of Compressed Gases and Their Containers, CGA P-22;
Safe Handling of Compressed Gases in Containers, CGA P-1; and
Use of Oxy-Fuel Gas Welding and Cutting Apparatus, CGA SB-83/4.

EUROPEAN COMMITTEE FOR STANDARDIZATION (CEN)

The European Committee for Standardization (CEN) is a regional standards organization that is similar in structure and scope to the International Organization for Standardization (ISO), but for a limited part of the world. CEN writes standards, but voting participation in the organization is limited to European countries. The objectives of the European Committee for Standardization (CEN) are to draw up voluntary European Standards and promote the corresponding conformity of products and services in areas other than electrotechnical and telecommunications. In particular, CEN has an agreement for technical cooperation (the Vienna Agreement) with the International Organization for Standardization (ISO).

The following countries are members of the European Committee for Standardization: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. The CEN affiliates are Albania, Bulgaria, Croatia, Cyprus, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia, and Turkey. In addition, CEN includes the following corresponding organizations: Egypt, South Africa, and Ukraine.

More information on CEN is available from:

European Committee for Standardization (CEN)
Rue de Stassart 36
B-1050 Brussels
Belgium
Telephone: + 32 2 550 0811
Web site: www.cenorm.be

INTERNATIONAL INSTITUTE OF WELDING (IIW)

The International Institute of Welding (IIW) was founded in 1948 by welding institutes or societies in 13 countries to promote international collaboration in welding. With 43 member countries in 2000, the organization's objectives are to promote the development of welding and to provide for the exchange of scientific and technical information on welding research and education, to assist in the formulation of international standards for welding in collaboration with the International Organization for Standardization (ISO), and to promote the organization of national welding associations.

The IIW has over 20 international groups of specialists that meet at least yearly on the invitation of one of the member countries. Besides hosting an international conference on some aspect of welding, these specialists spend three days annually in parallel sessions for meetings of the various commissions and other working groups. The Commissions and other working groups are organized by topic. The yearly meetings (as well as intermediate meetings) are used to stimulate research and disseminate information on welding processes, their application, and other associated subjects. Each year about 400 papers emanate from the IIW working units, some of which are published in the IIW journal, *Welding in the World*, while others become books dealing with recommended practices.

These technical discussions often form the technical basis for standards and have supplied the basis for the great majority of the welding standards issued by the

ISO over the past 30 years. Members of these working units and their employers therefore have a major influence over the content of such standards.

Since 1989, the IIW has been authorized by ISO to prepare the final texts of international welding standards as an international standardizing organization. The first ISO standards produced entirely by the IIW were published in 1990.

The American Welding Society is recognized by the IIW as the main member society for the United States. The responsibilities associated with this main-member status include the transmission of IIW documents to the IIW delegates and experts in the United States and serving as the secretariat for the American Council of the IIW.

The Welding Research Council (WRC) is the other member society representing the United States. The American Council of the IIW has served to bring together the various welding interests in the United States, including those within both AWS and the Welding Research Council, to select the official representatives for the various IIW working parties and to promote the transfer of information between U.S. experts and those in other countries.

Further information about the International Institute of Welding is available from:

International Institute of Welding (IIW)
Z1 Paris Nord II
BP 50362
95942 Roissy CDG Cedex
France
Telephone: 33 1 49 90 36 00
Web site: www.iiw_iis.org

UNITED STATES GOVERNMENT

Several departments of the federal government, including the General Services Administration, are responsible for developing welding standards or adopting existing standards, or both. It should be noted, however, that federal law has directed all government agencies to use commercial standards whenever possible. Compliance with this mandate is occurring gradually as standards are phased out and replaced. Therefore, it is important for users to ensure they are working with the latest edition of applicable codes and other standards.

Consensus Standards

The United States Departments of Labor, Transportation, and Energy are primarily concerned with adopting existing national consensus standards or creating separate standards, as necessary.

The Occupational Safety and Health Administration (OSHA) of the United States Department of Labor issues regulations promoting occupational safety and health protection. The welding-related portions of the standards adopted or established by OSHA are published under Title 29 of the *United States Code of Federal Regulations*. Part 1910 establishes occupational health and safety regulations for general industry, whereas Part 1926 prescribes standards for the construction industry. These regulations have been derived primarily from the national consensus standards published by the American National Standards Institute (ANSI) and the National Fire Protection Association (NFPA).

Similarly, the United States Department of Transportation (DOT) is responsible for regulating the transportation of hazardous materials, petroleum, and petroleum products by pipeline in interstate commerce. Its rules are published under Title 49 of the *United States Code of Federal Regulations,* Part 195. Typical of the many national consensus standards incorporated by reference in these regulations are the American Petroleum Institute's *Welding of Pipelines and Related Facilities,* ANSI/API 1104, and the American Society of Mechanical Engineers' *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids*, ASME B31.4. The U.S. Department of Transportation is also responsible for regulating merchant ships of American registry. It is empowered to control the design, fabrication, and inspection of these ships by Title 46 of the *United States Code of Federal Regulations*.

The United States Coast Guard is responsible for performing inspections of merchant ships. The *U.S.C. G. Marine Engineering Regulations* incorporate references to national consensus standards, such as those published by ASME, ANSI, and ASTM. These rules address repairs and alterations that must be performed with the cognizance of the local Coast Guard marine inspection officer.

The United States Department of Energy (DOE) is responsible for the development and use of standards by government and industry for the design, construction, and operation of safe, reliable, and economic nuclear energy facilities. National consensus standards, such as the ASME *Boiler and Pressure Vessel Code,* Sections III and IX, and the American Welding Society's *Structural Welding Code—Steel*, AWS D1.1, are referenced in full or in part.

The Nuclear Regulatory Commission (NRC) develops requirements and procedures that address the construction, operation, and safety of nuclear power generation plants and systems for organizations in the United States. The NRC also references codes and standards issued by ASME, AWS, and ASTM, adapting these documents through safety analysis reports (SAR). An explanation of this process as it applies to codes and standards is presented in *United States Code of Federal Regulations* 10 CFR 50.55a, "Codes and Standards," published by the Nuclear Regulatory Commission.

Military and Federal Standards and Specifications

Military specifications are prepared by the United States Department of Defense (DOD). They provide standards for materials, products, and services specifically for military use and for commercial items modified to meet military requirements. Military specifications have document designations beginning with the prefix MIL. They are issued as either coordinated or limited-coordination documents. Coordinated documents cover items or services required by more than one branch of the military. Limited coordination documents cover items or services of interest to a single branch. If a document is of limited coordination, the branch of the military that uses the document appears in parentheses in the document designation. It is important to note that DOD has begun to replace military specifications with consensus standards in the interest of economy.

Military and federal specifications often include requirements for the testing and approval of a material, process, or piece of equipment before its submission for use under the specification. If the acceptance tests pass the specification requirements, the material or equipment is included in the applicable *Qualified Products List (QPL)*. In other specifications, the supplier is responsible for product conformance. This is often the case for welded fabrications. The supplier must show evidence that the welding procedures and welding personnel are qualified in accordance with the requirements of the specification. The supplier must also certify the test report.

The following military and federal standards, which are listed in the United States Department of Defense Index, address welding, brazing, and soldering (standards that regulate base metals and welding equipment are not included):

Brazing Alloy, Silver, QQ-B-654;
Brazing, Oxyacetylene, of Built-Up Metal Structures, MIL-B-12673;
Electrode, Welding Covered (Austenitic Chromium-Nickel Steel, for Corrosive and High Temperature Services), MIL-E-22200/2;
Electrode, Welding, Bare, Copper and Copper Alloy, MIL-E-23765/3;
Electrode, Welding, Bare, Solid, Nickel-Manganese-Chromium-Molybdenum Alloy Steel for Producing HY-130 Weldments for As-Welded Applications, MIL-E-24355;
Electrode, Welding, Bare, Solid; and Fluxes, Submerged Arc Welding, Carbon and Low Alloy Steels, MIL-E-23765/4;
Electrode, Welding, Covered, Copper-Nickel Alloy, MIL-E-22200/4;
Electrode, Welding, Covered, Low-Hydrogen, and Iron Powdered Low-Hydrogen, Chromium-Molybdenum Alloy Steel and Corrosion-Resisting Steel, MIL-E-22200/8;
Electrode, Welding, Covered, Nickel Base Alloy, and Cobalt Base Alloy, MIL-E-22200/3;
Electrode, Welding, Flux Cored General Specification for, MIL-E-24403;
Electrode, Welding, Mineral Covered, Iron-Powder, Low-Hydrogen Medium and High Tensile Steel, As-Welded or Stress-Relieved Weld Application, MIL-E-22200/1;
Electrode, Welding, Mineral Covered, Low-Hydrogen or Iron-Powder, Low Hydrogen, Nickel-Manganese-Chromium-Molybdenum Alloy Steel for Producing HY-130 Weldments for As-Welded Applications, MIL-E-22200/9;
Electrode, Welding, Mineral Covered; Iron-Powder, Low-Hydrogen, High Tensile Low Alloy Steel Heat-Treatable Only, MIL-E-22200/5;
Electrode, Welding, Surfacing, Iron Base Alloy, MIL-E-19141;
Electrodes and Rods—Welding, Bare, Chromium and Chromium-Nickel Steels, MIL-E-19933;
Electrodes and Rods—Welding, Bare, Nickel Alloy, MIL-E-21562;
Electrodes and Rods—Welding, Bare, Solid and Alloyed Cored, General Specification for, MIL-E-23765;
Electrodes and Rods—Welding, Bare, Solid, Mild and Alloy Steel, MIL-E-23765/1;
Electrodes, Cutting and Welding, Carbon-Graphite, Uncoated and Copper-Coated, MIL-E-17777;
Electrodes, Welding, Covered, General Specification for, MIL-E-22200;
Electrodes, Welding, Mineral Covered, Iron-Powder, Low-Hydrogen Medium, High Tensile and Higher-Strength Low Alloy Steels, MIL-E-22200/10;
Electrodes, Welding, Mineral-Covered, Iron-Powder, Low-Hydrogen-8, Nickel-Chromium-Molybdenum-Vanadium Alloy Steel for Producing HY-130 Weldments to be Heat Treated, MIL-E-22200/11;
Fabrication, Welding, and Inspection of Ship Structure, MIL-STD-1689;
Flux, Soldering, Non Electrical, Paste and Liquid, A-A-51145;
Welded Joint Design, MIL-STD-22;
Welded Joint Designs, Armored Tank Type, Handbook for, MIL-HDBK-21;
Welded Joint, Inspection of, MIL-HDBK-1890;

Welding of Aerospace Ground Support Equipment and Related Facilities, Specification for, KSC-SPEC-5004;

Welding Rods and Electrodes, Packaging of, MIL-W-10430;

Welding, High Hardness Armor, MIL-STD-1185;

Welding, Resistance, Spot, Seam, and Projection, for Fabricating Assemblies of Low-Carbon Steel, MIL-W-12332;

Weldment, Aluminum and Aluminum Alloy, MIL-W-22248; and

Weldment, Steel, Carbon and Low Alloy (Yield Strength 30,000–60,000 psi), MIL-W-21157.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies, one from each of some 138 countries. This nongovernmental organization, which was established in 1947, has as its mission the promotion of the development of standardization and related activities in the world.

Many people erroneously assume that the term *iso* is an abbreviation. In fact, *iso* is a word that is derived from the Greek *isos*, meaning "equal." Thus, "ISO" is a short official title, not an acronym for the longer "International Organization for Standardization."

ISO interacts with the various countries in the world through other standards organizations. For the United States, these other organizations include: (1) national coordinators, such as the American National Standards Institute (administrator and coordinator of the United States' private-sector voluntary standardization system), (2) national standards bodies, some of which are authorized drafting bodies for ISO standards, and (3) individual technical advisory groups (TAGs), which develop national consensus responses to ISO ballots.

ISO also interacts with other international standards bodies, such as the International Electrotechnical Commission (IEC), the International Institute of Welding, and the European Committee for Standardization (CEN), which develops regional international standards, primarily for Europe.

Member bodies of ISO are the organizations that represent standardization interests in each country. Only one such body per country is accepted for membership. These member bodies have the following four principal tasks:

1. Inform interested parties of international standardization opportunities,
2. Develop a national position and represent it during international negotiation of standards agreements,
3. Ensure that a secretariat is provided for ISO technical committees of interest, and
4. Provide their country's share of ISO membership dues.

The technical work of ISO is carried out in a hierarchy of some 2700 technical committees, subcommittees, and working groups. In these committees, qualified representatives of organizations from all over the world come together as equal partners in the resolution of global standardization problems.

The responsibility for administering a standards committee is accepted by one of the national standards bodies that make up the ISO membership. The member body holding the secretariat of a standards committee normally appoints one or two persons to do the technical and administrative work. A committee chairperson assists committee members in reaching consensus. Generally, the term *consensus* means that a particular solution to the problem at hand derived by all interests is the best possible one for international application at that time. Although the greater part of the ISO technical work is done by correspondence, a dozen ISO meetings, on average, are taking place somewhere in the world on any given working day of the year.

The ISO Central Secretariat in Geneva, Switzerland ensures the flow of documentation in all directions; clarifies technical points with secretariats and chairpersons; and ensures that the agreements approved by the technical committees are edited, submitted as Draft International Standards (DIS) to ISO member bodies for voting, and published.

The standards issued by ISO have three major characteristics. First, they are consensual documents in that the views of all interests are taken into consideration. Second, they are implemented industry wide as they provide global solutions to satisfy industries and customers worldwide. Third, they are voluntary; that is, the use of these standards is based on the voluntary involvement of the buyers and sellers.

The technical committee of major interest to the welding community is TC 44 on Welding and Allied Processes. Its scope includes the standardization of welding, by all processes, as well as allied processes. These standards include terminology, definitions and the symbolic representation of welds on drawings, apparatus and equipment for welding, raw materials (gas, base, and filler metals), welding processes and procedures, methods of testing and control, calculations and the design of welded assemblies, the qualification of welders and welding operators, and safety and health. The scope of this committee excludes electrical safety matters related to welding, which are the responsibility of International Electrotechnical Commission (IEC)/TC 26.

The work of ISO Technical Committee (TC) 44 is divided into subcommittees and working groups as follows:

ISO/TC 44/WG 1, Underwater Welding;
ISO/TC 44/SC 3, Welding Consumables;
ISO/TC 44/SC 4, Arc Welding Equipment;
ISO/TC 44/SC 5, Testing and Inspection of Welds;
ISO/TC 44/SC 6, Resistance Welding;
ISO/TC 44/SC 7, Representation and Terms;
ISO/TC 44/SC 8, Equipment for Gas Welding, Cutting and Allied Processes;
ISO/TC 44/SC 9, Health and Safety;
ISO/TC 44/SC 10, Unification of Requirements in the Field of Metal Welding;
ISO/TC 44/SC 11, Approval Requirements for Welding and Allied Processes Personnel; and
ISO/TC 44/SC 12, Soldering and Brazing Materials.

The TC 44 Secretariat has responsibility for all standards prepared under the individual subcommittees and working groups.

Some welding issues fall within the scope of other technical disciplines. For example, TC 44 has a liaison with TC 135, Non-Destructive Testing, which handles the nondestructive examination of welds. The scope of this committee is standardization of nondestructive testing as applied generally to construction materials, components, and assemblies. The range of standards includes a glossary of terms, methods of testing, and performance specifications for testing equipment and ancillary apparatus.

ISO/TC 135, along with its subcommittees, is responsible for some 23 ISO standards. Twenty-nine countries participate in TC 135 as members, while another 35 serve as observers. The activities of TC 135 are divided by topic among five subcommittees: SC 2, Surface Methods; SC 3, Acoustical Methods; SC 4, Eddy Current Methods; SC 5, Radiation Methods; SC 6, Leak Detection Methods; SC 7, Personnel Qualification, and SC 8, Infrared Thermography for Nondestructive Testing

Further information is available from:

International Organization for Standardization (ISO)
1, Rue de Varembé, Case postale 56
CH-1211 Geneva 20, Switzerland
Telephone: + 41 22 749 01 11
Web site: www.iso.ch

PUBLICATIONS

ISO welding publications provide for the standardization of all welding and allied processes, except for those areas covered by the International Electrotechnical Commission (IEC), which is responsible for all aspects of international electrotechnical standardization, such as the standardization of welding power sources and accessories. The scope of these publications is broad. Major subject areas include welding terminology and definitions; symbolic representations; welding apparatus and equipment; raw materials (e.g., gas and filler metals); welding processes; testing and inspection methods; design of welded assemblies; personnel qualifications; health and safety; and electrical safety matters related to welding.

A complete and up-to-date listing of all ISO standards is available in the organization's on-line catalog (www.iso.ch). A partial listing of ISO standards that relate to welding is presented below; the documents have been grouped according to subcommittee for the sake of convenience:

WELDING CONSUMABLES (SC 3)

Arc Welding—Solid and Tubular Cored Wires Which Deposit Carbon and Carbon Manganese Steel—Dimensions of Wires, Spools, Rims and Coils, ISO 864;
Bare Solid Filler Rods for Oxy-Acetylene and Tungsten Inert Gas Arc (TIG) Welding, Depositing an Unalloyed or Low Alloyed Steel—Codification, ISO 636;
Covered Electrodes for Manual Arc Welding of Cast Iron—Symbolization, ISO 1071;
Covered Electrodes for Manual Arc Welding of Creep-Resisting Steels—Code of Symbols for Identification, ISO 3580;
Covered Electrodes for Manual Arc Welding of Stainless and Other Similar High Alloy Steels—Code of Symbols for Identification, ISO 3581;
Covered Electrodes—Determination of the Efficiency, Metal Recovery and Deposition Coefficient, ISO 2401;
Filler Materials for Manual Welding—Size Requirements, ISO 544;
Tungsten Electrodes for Inert Gas Shielded Arc Welding and for Plasma Cutting and Welding—Codification, ISO 6848;
Welding Consumables—Shielding Gases for Arc Welding and Cutting, ISO 14175; and
Welding—Determination of Hydrogen in Deposited Weld Metal Arising from the Use of Covered Electrodes for Welding Mild and Low Alloy Steels, ISO 3690.

TESTING AND INSPECTION OF WELDS (SC 5)

Fusion Welded Butt Joints in Steel—Transverse Root and Face Bend Test, ISO 5173;

Fusion Welded Butt Joints in Steel—Transverse Side Bend Test, ISO 5177;
Fusion-Welded Butt Joints in Steel—Transverse Tensile Test, ISO 4136;
Fusion-Welded Butt Joints in Steel—Transverse Tensile Test, ISO 4136;
Radiographic Image Quality Indicators for Non-Destructive Testing—Principles and Identification; ISO 1027;
Recommended Practice for Radiographic Examination of Fusion Welded Joints, ISO 1106;
Recommended Practice for the X-Ray Inspection of Fusion Welded Butt Joints for Aluminum and Its Alloys and Magnesium and Its Alloys 5 to 50 mm Thick, ISO 2437; and
Welds in Steel—Calibration Block No. 2 for Ultrasonic Examination of Welds, ISO 7963.

RESISTANCE WELDING (SC 6)

Graphical Symbols for Resistance Welding Equipment, ISO 7286;
Projections for Resistance Welding, ISO 8167;
Resistance Welding—Resistance Welding Equipment—Mechanical and Electrical Requirements, ISO 669; and
Welding—Materials for Resistance Welding Electrodes and Ancillary Equipment, ISO 5182.

REPRESENTATION AND TERMS (SC 7)

Weldability—Definition, ISO 581;
Welded, Brazed and Soldered Joints—Symbolic Representation on Drawings, ISO 2553;
Welding and Allied Processes—Classification of Geometric Imperfections in Metallic Materials, ISO 6520;
Welding and Allied Processes—Recommendation for Joint Preparation, ISO 9692;
Welding and Allied Processes—Vocabulary, ISO 857; and
Welds—Working Positions—Definitions of Angles of Slope and Rotation, ISO 6947.

EQUIPMENT FOR GAS WELDING, CUTTING AND ALLIED PROCESSES (SC 8)

Gas Welding Equipment—Pressure Regulators for Gas Cylinders Used in Welding, Cutting and Allied Processes up to 300 Bar, ISO 2503;
Gas Welding Equipment—Hose Connections for Equipment for Welding, Cutting and Allied Processes, ISO 3253;
Gas Welding Equipment—Rubber Hoses for Welding, Cutting and Allied Processes, ISO 3821;
Pressure Gauges Used in Welding, Cutting and Allied Processes, ISO 5171;
Equipment Used in Gas Welding, Cutting and Allied Processes—Safety Devices for Fuel Gases and Oxygen or Compressed Air—General Specifications, Requirements and Tests, ISO 5175;
Quick-Action Couplings with Shut-Off Valves for Gas Welding, Cutting and Allied Processes, ISO 7289;
Gas Welding Equipment—Pressure Regulators for Manifold Systems Used in Welding, Cutting and Allied Processes up to 300 Bar, ISO 7291;
Flowmeter Regulators Used on Cylinders for Welding, Cutting and Allied Processes—Classification and Specifications, ISO 7292;
Gas Welding Equipment—Specification for Hose Assemblies for Equipment for Welding, Cutting and Allied Processes, ISO 8207; and
Gas Welding Equipment—Acetylene Manifold Systems for Welding, Cutting and Allied Processes—General Requirements, ISO 14114.

HEALTH AND SAFETY (SC 9)

Health and Safety in Welding and Allied Processes—Sampling of Airborne Particles and Gases in the Operator's Breathing Zone, ISO 10882.

UNIFICATION OF REQUIREMENTS IN THE FIELD OF METAL WELDING (SC 10)

Arc-Welded Joints in Aluminum and Its Weldable Alloys—Guidance on Quality Levels for Imperfections, ISO 10042;
Arc-Welded Joints in Steel—Guidance on Quality Levels for Imperfections, ISO 5817;
Quality Requirements for Welding—Fusion Welding of Metallic Materials, ISO 3834;
Quality Requirements for Welding—Resistance Welding of Metallic Materials, ISO 14554,
Specification and Approval of Welding Procedures for Metallic Materials, ISO 9956;
Welding—Acceptance Inspection of Electron Beam Welding Machines, ISO 14744;
Welding—Electron and Laser-Beam Welded Joints—Guidance on Quality Levels for Imperfections; ISO 13919;
Welding—Friction Welding of Metallic Materials, ISO 15620; and
Welding—Guidelines for a Metallic Materials Grouping System, ISO/TR 15608.

APPROVAL REQUIREMENTS FOR WELDING AND ALLIED PROCESSES PERSONNEL (SC 11)

Approval[1] *Testing of Welders—Fusion Welding,* ISO 9606;
Welding Coordination—Tasks and Responsibilities, ISO 14731; and
Welding Personnel—Approval Testing of Welding Operators for Fusion Welding and of Resistance Weld Setters for Fully Mechanized and Automatic Welding of Metallic Materials, ISO 14732.

SOLDERING AND BRAZING MATERIALS (SC 12)

Filler Metal for Soft Soldering, Brazing and Braze Welding—Designation, ISO 3677;
Soft Solder Alloys—Chemical Compositions and Forms, ISO 9453;
Soft Soldering Fluxes—Classification and Requirements, ISO 9454;
Soft Soldering Fluxes—Test Methods, ISO 9455;
Solder Wire, Solid and Flux Cored—Specification and Test Methods, ISO 12224; and
Soldering and Brazing Materials—Methods for the Sampling of Soft Solders for Analysis, ISO 10564.

NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS (NBBPVI)

The National Board of Boiler and Pressure Vessel Inspectors (NBBPVI), often referred to simply as the "National Board," represents the enforcement agencies empowered to assure adherence to the ASME *Boiler and Pressure Vessel Code*. Its members are the chief inspectors or other jurisdictional authorities that administer the boiler and pressure vessel safety laws in the various jurisdictions of the United States and provinces of Canada.

The National Board is involved in the inspection of new boilers and pressure vessels. It maintains a registration system for use by manufacturers that desire or are required by law to register the boilers or pressure vessels that they have constructed. This organization is also responsible for investigating possible violations of the ASME *Boiler and Pressure Vessel Code* by either commissioned inspectors or manufacturers.

In some states and other jurisdictions, it is required that all repairs and alternations to boilers and pressure vessels built to the ASME *Boiler and Pressure Vessel Code* be made in accordance with the *National Board Inspection Code*, NB-23, which is written and published by the National Board. To be permitted to make repairs and alterations to such components, the repair organization must prepare a quality control program. This program and its implementation must be audited by the National Board. Upon the successful completion of the audit, the National Board issues a Repair Stamp (R-Stamp) authorization to the repair organization. Any welding that is to be performed during the repair or alteration must first be qualified to *Welding and Brazing Qualifications*, Section IX of the ASME *Boiler and Pressure Vessel Code*.

Further information is available from:

National Board of Boiler and Pressure Vessel Inspectors
1055 Crupper Avenue
Columbus, OH 43229-1183
Telephone: (614) 888-8320
Web site: www.nationalboard.org

Publications

The National Board, with headquarters in Columbus, Ohio, publishes a number of pamphlets and forms concerning the manufacture and inspection of boilers, pressure vessels, and safety relief valves. It also publishes the *National Board Inspection Code,* NB 23, for the guidance of its members, commissioned inspectors, and others. The purpose of this code is to maintain the integrity of boilers and pressure vessels after they have been placed in service by providing rules and guidelines for inspection after installation, repair, alteration, or rerating. In addition, it provides inspection guidelines for authorized inspectors during the fabrication of boilers and pressure vessels.

National Board authorized stamp holders are listed in the publication *Manufacturers and National Board Repair Certificate Holders Directory,* NB 20.

NATIONAL FIRE PROTECTION ASSOCIATION (NFPA)

The mission of the National Fire Protection Association (NFPA) is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating scientifically based consensus codes and standards, research, training, and education. The National Fire Protection Association publishes standards that present general principles for the installation of gas supply systems and the storage and handling of the gases commonly used in welding and cutting.

NFPA installation standards require that welding procedures and welders be qualified to the *Standard for Welding Procedure and Performance Qualification,* AWS B2.1, or to *Welding and Brazing Qualifications,* Section IX of the ASME *Boiler and Pressure Vessel Code*. NFPA also issues standards related to the safe use of welding and cutting processes.

1. This term is equivalent to *qualification* in the United States.

Further information about the National Fire Protection Association can be obtained from:

National Fire Protection Association (NFPA)
1 Battery March Park
P.O. Box 9101
Quincy, MA 02269-9101
Telephone: (617) 770-3000
Web site: www.nfpa.org

Publications

NFPA standards are widely used as the basis of legislation and regulation at all levels of government. Many are referenced in the regulations of the Occupational Safety and Health Administration (OSHA). NFPA standards are also used by insurance authorities for risk evaluation and premium rating.

NFPA publishes several standards and handbooks that present general principles for the installation of gas supply systems and the storage and handling of gases commonly used in welding and cutting. A partial listing of these welding-related publications is presented below:

"Installation of LP-Gas Systems," Chapter 3 in *Liquefied Petroleum Gas Code,* 3rd edition;
"Piping Systems," Chapter 3 in *Flammable and Combustible Liquids Code,* NFPA 30;
Control of Flammable and Combustible Liquids and Gases in Manholes, Sewers, and Similar Underground Structures, NFPA 328;
Gas Piping Installation, Part 3, in *National Fuel Gas Code,* NFPA 54;
Gas Piping System Design, Materials, and Components, Part 2, in *National Fuel Gas Code,* NFPA 54;
Liquified Petroleum Gas Code, NFPA 58; and
National Fuel Gas Code, NFPA 54.

PIPE FABRICATION INSTITUTE (PFI)

The Pipe Fabrication Institute (PFI) was formed in 1913 with the purpose of promoting uniformity and quality in the pipe fabrication industry. PFI standards address areas not specifically covered by codes. PFI technical bulletins and other publications are not mandatory but are intended to assist the piping fabricator in meeting code requirements. PFI publishes standards related to engineering and design, welding, fabrication, cleaning, painting, shipping, examination, testing and quality control.

Further information about the Pipe Fabrication Institute is available from:

Pipe Fabrication Institute (PFI)
655 - 32nd Avenue, Suite 201
Lachine, Qc., Canada, H8T 3G6
Telephone: (514) 634-3434
Web site: www.pfi-institute.org

Publications

The Pipe Fabrication Institute publishes numerous documents for use by the piping industry. Some of the standards have mandatory status because they are referenced in one or more piping codes. The purpose of PFI standards is to promote uniformity of piping fabrication in areas not specifically covered by codes. Other PFI documents, such as technical bulletins, are not mandatory, but they aid the piping fabricator in meeting the requirements of codes.

The following partial listing of PFI standards relate directly to welding:

Internal Machining and Fit-Up of GTAW Root Pass Circumferential Butt Welds, ES21;
Internal Machining and Solid Machined Backing Rings for Circumferential Butt Welds, ES1;
Minimum Length and Spacing for Welded Nozzles, ES7; and
Nonsymmetrical Bevels and Joint Configurations for Butt Welds, ES35.

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)

Founded in 1905, the Society of Automotive Engineers, along with its Aerospace Materials Specifications (AMS) division, publishes welding standards for use by the automotive and aerospace industries. Included are ISO and welding-related standards along with numerous technical and research-related papers.

On January 16, 1974, the Society of Automotive Engineers and the American Welding Society formed a joint committee to facilitate the development and publication of documents related to the selection, practice and procedure specification, use, and testing of welding materials and welded products. These publications apply to many industries, including the automotive, agricultural machinery, aerospace, and ground support equipment industries, among others.

Further information on this organization is available from:

SAE World Headquarters
400 Commonwealth Drive
Warrendale, PA 15096-0001
Telephone: (724) 776-4841
Web site: www.sae.org

Publications

A partial listing of the Society of Automotive Engineers' welding-related publications categorized by topic is presented below:

AUTOMOTIVE STANDARDS

Recommended Practices for Automotive Weld Quality—Resistance Spot Welding, ANSI/AWS D8.7;
Recommended Practices for Test Methods for Evaluating the Resistance Spot Welding Behavior of Automotive Sheet Steel Materials, ANSI/AWS D8.9;
Specification for Automotive and Light Truck Components' Weld Quality—Arc Welding, ANSI/AWS D8.8; and
Standard for Automotive Resistance Spot Welding Electrodes, AWS D8.6.

AEROSPACE MATERIAL SPECIFICATIONS

Brazing, Aluminum Torch Aluminum Alloys Molten Flux (Dip), AMS 2673;
Brazing, Copper, AMS 2670;
Brazing, Silver for Small Pressurized Fittings, AMS 2667;
Brazing, Silver, for Use up to 400°F (204°C), AMS 2665;
Brazing, Silver, for Use up to 800°F (427°C), AMS 2664;
Electron-Beam Welding for Fatigue Critical Applications, AMS 2680;
Nickel Alloy Brazing, AMS 2675;
Repair Welding of Aerospace Castings, AMS 2694;
Welding, Electron-Beam, AMS 2681; and
Welding, Tungsten Arc, Inert Gas (GTAW Method), AMS 2685.

FLUX

Brazing Filler Metal, Paste, Copper, Water Thinning, AMS 3430.
Flux Aluminum Dip Brazing 1030°F (554°C) or Lower Liquidus, AMS 3415;
Flux, Aluminum Brazing for Torch or Furnace Brazing, AMS 3412;
Flux, Aluminum Dip Brazing, 1090°F (588°C), Fusion Point, AMS 3416;
Flux, Aluminum Welding, AMS 3414;
Flux, Silver Brazing, AMS 3410; and
Flux, Silver Brazing High-Temperature, AMS 3411.

ALUMINUM ALLOYS

Aluminum Alloy, Welding Wire 4.1Si – 0.20Mg (4643), AMS 4189;
Aluminum Alloy, Welding Wire 4.5Cu – 0.70Ag – 0.30Mn – 0.25Mg – 0.25Ti (201), AMS 4233;
Aluminum Alloy, Welding Wire 5.0Si – 12Cu – 0.50Mg (355), AMS 4245;
Aluminum Alloy, Welding Wire 5.2Si (4043), AMS 4190;
Aluminum Alloy, Welding Wire 7.0Si – 0.52Mg (357), AMS 4246.
Aluminum Alloy, Welding Wire, 6.3Cu – 0.30Mn – 0.18Zr – 0.15Ti – 0.10V (2319), AMS 4191;
Aluminum Alloys, Welding Wire 7.0Si – 0.38Mg – 0.10Ti (4008), AMS 4181;
Filler Metal, Aluminum Brazing, 10Si – 4.0Cu (4145), AMS 4184; and
Filler Metal, Aluminum Brazing, 12Si (4047), AMS 1485.

MAGNESIUM ALLOYS

Magnesium Alloy Welding Wire 3.3Ce – 2.5Zn – 0.72Zr (EZ33A), AMS 4363; and
Magnesium Alloy Welding Wire 9.0Al – 2.0Zn (AZ92A), AMS 4395.

BRAZING AND SOLDERING FILLER METALS

Cobalt Alloy, High Temperature Brazing Filler Metal, 50Co – 8.0Si – 19/cr – 17Ni – 4.0W – 0.80B, 2050–2100°F (1121 to 1149°C) Solidus-Liquidus Range, AMS 4783;
Cooper Alloy, Brazing Filler Metal 52.5Cu – 38Mn – 9.5Ni 1615 to 1700°F (879 to 927°C) Solidus-Liquidus Range, AMS 4764;
Gold-Nickel Alloy Brazing Filler Metal, High Temperature, 82Au – 18Ni 1740°F (949°C) Solidus-Liquidus Temperature, AMS 4787;
Gold-Palladium-Nickel Alloy Brazing Filler Metal, High Temperature, 50Au – 25Pd – 25Ni, 2015 to 2050°F (1102 to 1121°C) Solidus-Liquidus Range, AMS 4784;
Gold-Palladium-Nickel Alloy Brazing Filler Metal, High Temperature 30Au – 34Pd – 36Ni 2075 to 2130°F (1135 to 1166°C) Solidus-Liquidus Range, AMS 4785;
Gold-Palladium-Nickel Alloy Brazing Filler Metal, High Temperature, 70Au – 8.0Pd – 22Ni 1845 to 1915°F (1007 to 1046°C), AMS 4786;
Manganese Alloy Brazing Filler Metal 66Mn – 16NI – 16Co – 0.80B 1770 to 1875°F (966 to 1024°C) Solid-Liquidus Range, AMS 4780;
Nickel Alloy, Brazing Filler Metal 71Ni – 10Si – 19Cr 1975 to 2075°F (1080 to 1135°C) Solidus-Liquidus Range, AMS 4782;
Nickel Alloy, Brazing Filler Metal 73Ni – 0.75C – 4.5Si – 14Cr – 3.1F 4.5Fe, 1790 to 1970°F (977 to 1077°C) Solidus-Liquidus Range, AMS 4775;
Nickel Alloy, Brazing Filler Metal 73Ni – 4.5Si – 14Cr – 3.1B – 4.5Fe (Low Carbon) 1790 to

1970°F (977 to 1077°C) Solidus-Liquidus Range, AMS 4776;

Nickel Alloy, Brazing Filler Metal 82Ni – 4.5Si – 7.0Cr – 3.1B – 3.0Fe, 1780 to 1830°F (971 to 999°C) Solidus-Liquidus Range, AMS 4777;

Nickel Alloy, Brazing Filler Metal 92Ni – 4.5Si – 3.1B, 1800 to 1900°F Solidus-Liquidus Range, AMS 4778;

Nickel Alloy, Brazing Filler Metal 94Ni – 3.5Si – 1.8B 1800 to 1950°F (982 to 1066°C) Solidus-Liquidus Range, AMS 4779;

Silver Alloy Brazing Filler Metal 50Ag – 24Cd – 16Zn – 15.5Cu 1160 to 1175°F (627 to 635°C) Solidus-Liquidus Range, AMS 4770;

Silver Alloy Brazing Filler Metal 63Ag – 28.5Cu – 6.0Sn – 2.5Ni 1275 to 1475°F (691 to 802°C) Solidus-Liquidus Range, AMS 4774;

Silver Alloy, Brazing Filler Metal 35Ag – 26Cu – 21Zn – 18Cd 1125 to 1295°F (607 to 702°C) Solidus-Liquidus Range, AMS 4768;

Silver Alloy, Brazing Filler Metal 45Ag – 24Cd – 16Zn – 15Cu 1125 to 1145°F (607 to 618°C) Solidus-Liquidus Range, AMS 4769;

Silver Alloy, Brazing Filler Metal 50Ag – 16Cd – 15.5Zn 15.5Cu – 3.0Ni 1170 to 1270°F (632 to 688°C) Solidus-Liquidus Range, AMS 4771;

Silver Alloy, Brazing Filler Metal 54Jag – 40Cu 5.0Zn – 1.0Ni 1325 to 1575°F (718 to 857°C) Solidus-Liquidus Range, AMS 4772;

Silver Alloy, Brazing Filler Metal 56Ag – 42Cu – 2.0Ni 1420 to 1640°F (771 to 893°C) Solidus-Liquidus Range, AMS 4765;

Silver Alloy, Brazing Filler Metal 60Ab – 30Cu – 10Sn 1115 to 1325°F (602 to 718°C) Solidus-Liquidus Range, AMS 4773;

Silver Alloy, Brazing Filler Metal 85Ag – 15Mn 1760 to 1780°F (960 to 971°C) Solidus-Liquidus Range, AMS4766; and

Silver Alloy, Brazing Filler Metal 92.5Ag – 7.2Cu – 0.22Li 1435 to 163°F (779 to 891°C) Solidus-Liquidus Range, AMS 4767.

TITANIUM ALLOYS

Titanium Welding Wire, 5A1 – 2.5Sn, AMS 4953;

Titanium Welding Wire, 6A – 4V, AMS 4954;

Titanium Welding Wire, 6Al – 2Sn- 4Zr – 2Mo, AMS 4952;

Titanium Welding Wire, 8A1 – 1Mo – 1V, AMS 4953; and

Titanium Welding Wire, Commercially Pure, Environment-Controlled Packaging, AMS 4951.

CARBON STEELS

Steel, Welding Wire, 1.05Cr – 0.55Ni – 1.0Mo – 0.08V (0.26–0.32C), Vacuum Melted, Environment-Controlled Packaging, AMS 5027;

Steel, Welding Wire, 1.05Cr – 0.55Ni – 1.0Mo – 0.07V (0.34–0.40C), Vacuum Melted, Environment-Controlled Packaging (USN K23725), AMS 5028;

Steel, Welding Wire 0.78Cr – 1.8Ni – 0.35Mo – 0.20V (0.33–0.38), Vacuum Melted, Environment-Controlled Packaging, AMS 5029;

Steel, Welding Wire 0.06 Carbon, Maximum, AMS 5030; and

Welding Electrodes, Covered, Steel 0.07–0.15C, AMS 5031.

LOW-ALLOY STEELS

Steel Welding Wire, 0.59Cr – 0.2V (0.28–0.33C) *(SAE 6130) Vacuum Melted, Environment-Controlled Packaging,* AMS 6461;

Steel Welding Wire, 0.65SI – 1.25Cr – 0.50Mo – 0.30V (0.28–0.33C) Vacuum Melted, Environment-Controlled Packaging, AMS 6458;

Steel Welding Wire, 0.9Cr – 0.20Mo (0.28–0.33C) *(SAE 4130) Vacuum Melted, Environment-Controlled Packaging,* AMS 6457;

Steel Welding Wire, 1.0Cr – 10Ni – 3.8Co – 0.45Mo – 0.08V (0.14–0.17C) Vacuum Melted, Environment-Controlled Packaging, AMS 6468;

Steel, Corrosion Resistant, Welding Wire 5.2Cr – 0.52Mo, AMS 6466;

Steel, Welding Electrodes, Covered, 1.5Mo – 0.20V (0.06–0.12C) Vacuum Melted, AMS 6464;

Steel, Welding Electrodes, Covered, 5Cr – 0.55Mo (Noncurrent August 1999*),* AMS 6467;

Steel, Welding Wire, 0.95Cr – 0.20V (0.28–0.33C) (SAE 6130), AMS 6462;

Steel, Welding Wire, 1.0Cr – 1.0Mo – 0.12V (0.78–0.23C), Vacuum Melted, AMS 6460;

Wire, Steel Welding, 0.75Si 0.62Cr 0.20Mo 0.10Zr (0.1–0.17C), AMS 6460;

Wire, Steel Welding, 18.5Ni – 8.5Co – 5.2Mo – 0.72Ti – 0.10Al, Vacuum Melted, Environment-Controlled Packaging, AMS 6463; and

Wire, Steel Welding, 2.0Cr – 10Ni – 8.0Co – 1.0Mo – 0.02Al – 0.06V (0.10–0.14C), Vacuum Melted, Environment-Controlled Packaging, AMS 6465.

CORROSION- AND HEAT-RESISTANT STEELS AND ALLOYS

Alloy Welding Wire, Corrosion and Heat Resistant 75Ni – 15.5Cr – 8.0Fe, AMS 5683;

Cobalt Alloy, Corrosion and Heat Resistant, Hard Facing Rods and Wire, 62Co – 29Cr – 4.5W – 1.2C, AMS 5788;

Iron Alloy, Corrosion and Heat Resistant, Welding Wire 31Fe – 21Cr – 20Ni – 20Co – 3.0Mo – 2.5W – 1.0Cb – 0.15N Annealed, AMS 5794;

Nickel Alloy, Corrosion and Heat Resistant, Covered Welding Electrodes 48Ni – 22Cr – 1.5Co – 9.0Mo – 0.60W – 18.5Fe (Cancelled Apr 1996), AMS 5799;

Steel Welding Electrodes, Covered, Corrosion and Heat Resistant, 19.5Cr – 8.8Ni – 0.50Mo – 1.5W – 1.0Cb, AMS 5783;

Steel Welding Electrodes, Covered, Corrosion and Moderate Heat Resistant 15.5Cr – 4.5Ni – 2.9Mo – 0.10N, AMS 5781;

Steel, Corrosion and Heat Resistant, Welding Wire 11.8Cr – 2.8Ni – 1.6Co – 1.8Mo – 0.32V Vacuum Induction Melted, AMS 5822;

Steel, Corrosion and Heat Resistant, Welding Wire 11.8Cr – 2.8Ni – 1.6Co – 1.8Mo – 0.32V, AMS 5823;

Steel, Corrosion and Heat Resistant, Welding Wire 12.5Cr (SAE 51410), AMS 5776;

Steel, Corrosion and Heat Resistant, Welding Wire 13Cr – 8.0Ni – 2.3Mo – 1.1Al Vacuum Melted, AMS 5840;

Steel, Corrosion and Heat Resistant, Welding Wire 15Cr – 25.5Ni – 1.3Mo – 2.2Ti – 0.006B – 0.30V, AMS 5804;

Steel, Corrosion and Heat Resistant, Welding Wire 15Cr – 25.5Ni – 1.2Mo – 2.1Ti – 0.004B – 0.30V, Vacuum Induction Melted, Environment-Controlled Packaging, AMS 5805;

Steel, Corrosion and Heat Resistant, Welding Wire 15Cr – 30Ni – 1.2Mo – 2.2Ti – 0.25Al – 0.001B – 0.30V (0.01–0.03C), Vacuum Induction Melted, Environment-Controlled Packaging, AMS 5811;

Steel, Corrosion and Heat Resistant, Welding Wire 15Cr – 5.1Ni – 0.30Cb – 3.2Cu, AMS 5825;

Steel, Corrosion and Heat Resistant, Welding Wire 15Cr – 7.1Ni – 2.4Mo – 1.0Al Vacuum Melted, AMS 5812;

Steel, Corrosion and Heat Resistant, Welding Wire 16.4Cr – 4.8Ni – 0.22Cb – 3.6Cu, AMS 5825;

Steel, Corrosion and Heat Resistant, Welding Wire 16.5Cr – 4.5Ni – 2.9Mo – 0.10N, AMS 5774;

Steel, Corrosion and Heat Resistant, Welding Wire 18.5Cr – 11Ni – 0.40Cb (SAE 30347), AMS 5680;

Steel, Corrosion and Heat Resistant, Welding Wire 19Cr – 12.5Ni - 2.5Mo, High Ferrite Grade, AMS 5696;

Steel, Corrosion and Heat Resistant, Welding Wire 20.5Cr – 9.0Ni – 0.50Mo – 1.5W – 1.2Cb – 0.20Ti Vacuum Induction Melted, AMS 5782;

Steel, Corrosion and Heat Resistant, Welding Wire 20Cr, AMS 5790;

Steel, Corrosion and Heat Resistant, Welding Wire 27Cr – 21.5Ni, AMS 5694;

Steel, Corrosion and Heat Resistant, Welding Wire 29Cr – 9.5, AMS 5784;

Steel, Corrosion and Moderate Heat Resistant, Welding Wire 13Cr – 2.0Ni – 3.0W, AMS 5817;

Steel, Corrosion and Moderate Heat Resistant, Welding Wire 15.5Cr – 4.5Ni – 2.9Mo – 0.10N, AMS 5780;

Steel, Corrosion Resistant, Covered Welding Electrodes 12.5Cr, AMS 5694;

Steel, Corrosion Resistant, Welding Wire 12Cr (SAE 51410 Modified) Ferrite Control Grade, AMS 5821; and

Steel, Corrosion Resistant, Welding Wire 17Cr – 7.1Ni, 1.0Al, AMS 5824.

(SAE) AEROSPACE RECOMMENDED PRACTICES (ARP) OF INTEREST

Electron Beam Welding, ARP 1317; and

Welding of Structures for Ground Support Equipment, ARP 1330.

UNDERWRITERS LABORATORIES (UL)

Founded in 1894, Underwriters Laboratories, Incorporated (UL) is a not-for-profit organization that establishes, maintains, and operates laboratories to examine various products, systems, and materials to ascertain their safety. The organization also publishes standards, classifications, and specifications for these products, systems, and materials.

Underwriters Laboratories, Inc. develops standards with the participation of the public and organizations concerned with product safety, including consumers, persons associated with consumer-oriented organizations, academics, government officials, industrial and commercial users, inspection authorities, and insurance interests.

Further information about Underwriters Laboratories, Inc. can be obtained from:

Underwriters Laboratories, Inc.
333 Pfingsten Road
Northbrook, IL 60062
Telephone: (312) 272-8800
Web site: www.ul.com

Publications

Underwriters Laboratories, Inc. publishes the following standards of interest to the welding community:

Tanks, Steel Aboveground, for Flammable and Combustible Liquids, UL 58;
Tanks, Steel Underground forFlammable and Combustible Liquids, UL 142; and
Transformer Type Arc-Welding Machines, UL 551.

MANUFACTURER ASSOCIATIONS

A number of associations representing the manufacturers of welding and welding-related equipment and materials publish literature that is of interest to the welding community. These are listed below:

The Aluminum Association
900 19th Street, NW
Washington, DC 20006
Telephone: (202) 862-5100
Web site: www.aluminum.org

American Iron and Steel Institute (AISI)
1101 17th Street, NW, Suite 1300
Washington, DC 20036
Telephone: (202) 452-7100
Web site: www.steel.org

Copper Development Association, Incorporated
260 Madison Avenue
New York, NY 10016
Telephone: (212) 251-7200
Web site: www.copper.org

Electronic Industries Alliance
2001 I Street, NW
Washington, DC 20006
Telephone: (202) 457-4900
Web site: www.eia.org

National Electrical Manufacturers Association (NEMA)
1300 North 17th Street, Suite 1847
Rosslyn, VA 22209
Telephone: (703) 841-3200
Web site: www.nema.org

Resistance Welders Manufacturers Association (RWMA)
1900 Arch Street
Philadelphia, PA 19103
Telephone: (215) 564-3484
Web site:www.rwma.org

GUIDELINES FOR PARTICIPATING IN INTERNATIONAL STANDARDS ACTIVITIES

Few individuals have the funding or the time to attend international meetings in support of international standards activities. However, anyone in the United States who wishes to participate in international standards activities can do so in a number of ways. First, those interested in supporting international standards initiatives can participate in a technical advisory group (TAG). Various U.S. organizations collect responses to international ballots. Among those that address welding issues are the American Welding Society, which administers the U.S. TAG to ISO TC 44; ASQ, which administers the U.S. TAG to ISO TC 176 (ISO 9000 series); and ASTM, which administers the U.S. TAG to ISO TC 135.

Interested individuals can also read the reports compiled on the convocation of international meetings. These reports are published in various technical journals. In addition, the Annual Reports of the Commissions of the International Institute of Welding (written by the U.S. Delegates) are available through the American Council of the IIW.

The venues for international meetings often move from country to country. Occasionally, these meetings are held in the United States (for example, ISO TC 44 met in the United States in 1977, and ISO TC 164 met in the United States in 1998). Interested parties should look for meetings that are held in convenient locations. It is advisable to check calendars for upcoming meetings and learn if these are open to the public.

It is preferable to attend an international committee meeting in person, especially when representing a position. Although written comments are accepted by these committees, they are sometimes not persuasive because the committee may be unclear on some aspect. It may be difficult to justify the cost of trips to these meetings, but attending in person allows interested individuals to respond to questions and clarify a point of view. The U.S. Delegate can be contacted with respect to the rules and opportunities that exist.

CONCLUSION

Technological advances are prompting many changes in the ways codes and standards are written, delivered, and used. As computers become increasingly important to the welding industry, computer-related concerns are being incorporated into more welding standards. While those involved in manufacturing and industry might wish for fewer record-keeping requirements, the trend is clearly in the opposite direction. Not only are more codes and standards being developed, but existing documents continue to be revised and expanded. Thus, it is essential to remain up-to-date with the rules and procedures prescribed by the latest applicable codes and other standards.

SUPPLEMENTARY READING LIST

American Welding Society (AWS). *AWS 2000 Catalog*. Miami: American Welding Society.

Irving, Bob. 1999. International standardization: A wake-up call for American welders. *Welding Journal* 78(9): 35–39.

CHAPTER 17

SAFE PRACTICES

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CHAPTER 17

SAFE PRACTICES

INTRODUCTION

Health and safety considerations are paramount in all welding, cutting, brazing, and related processes. No activity is satisfactorily completed if personal injury or property damage occurs. This chapter presents an overview of the rules, regulations, and techniques that are implemented to minimize the safety hazards associated with welding, cutting, and allied processes. It examines safety management, the protection of personnel and the work area, process-specific safety considerations, and robotic safety.

The limited scope of this discussion precludes an exhaustive examination of the health and safety considerations related to all welding processes, particularly those involving sophisticated technology. Additional safety and health information relating to the various welding processes is presented in the American National Standard *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1,[1, 2] and in *Safety and Health Fact Sheets*,[3] the latter of which is available electronically at http://www.aws.org. Further process-specific information is published in *Welding Processes,*[4] Volume 2 of the American Welding Society's (AWS) *Welding Handbook,* 8th edition. The reader is encouraged to consult these sources and others listed in the Bibliography and Supplementary Reading List at the end of this chapter.

1. American National Standards Institute (ANSI) Accredited Standards Committee Z49, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1, Miami: American Welding Society.
2. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. American Welding Society (AWS) Project Committee on Labeling and Safe Practices, 1998, *Safety and Health Fact Sheets,* 2nd ed., Miami: American Welding Society (also available on line at http://www.aws.org).
4. O'Brien, R. L., ed., 1991, *Welding Processes,* Vol. 2 of *Welding Handbook,* 8th ed., Miami: American Welding Society.

SAFETY MANAGEMENT

According to estimates made by the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA), over 30 million U.S. workers are potentially exposed to one or more chemical hazards from approximately 650,000 hazardous chemical products in the workplace. As these numbers increase with the growing workforce and the introduction of hundreds of new products annually, this situation poses a serious problem for exposed workers and their employers.[5] Of these workers, an estimated 562,000 are at risk for exposure to chemical and physical hazards associated with welding, cutting, and brazing and related activities. Risks include injury from explosion, asphyxiation, electrocution, falling and crushing, and weld flash (burn to the eyes) as well as health hazards associated with overexposure to fumes, gases, or radiation produced or released during welding and related activities. These include lung disease, heavy metal poisoning, and metal fume fever, among others.[6]

The *Occupational Safety and Health Act* of 1970[7] was promulgated to ensure safe and healthy working conditions for all workers by providing for the transmission of information, training, education, and research in the field of occupational health and safety. OSHA's current standards for the welding, cutting and brazing in general industry and construction are based on the 1967 American National Standards Institute (ANSI) standard Z49.1 and the National Fire Protection

5. Occupational Health and Safety Administration (OSHA), 1993, *OSHA Fact Sheet 93-26, Hazard Communication Standard, 29 CFR 1910.1200* (available on line at http://www.osha-slc.gov/OshDoc/Fact_data/FSNO93-26.html).
6. Occupational Safety and Health Administration (OSHA), 1999, *Welding, Cutting, and Brazing* (available on line at http://www.osha.gov/oshainfo/priorities/welding).
7. *Occupational Safety and Health Act,* 1970, 91st Congress, Public Law 91-596, Washington D.C.: Superintendent of Documents, U.S. Government Printing Office.

Association's (NFPA) *Standard for Fire Prevention in Use of Cutting and Welding Processes,* NFPA 51B-1962.[8] Although these standards have undergone several revisions, the OSHA rules presented in the latest edition of Subpart Q of Title 29 *Code of Federal Regulations* (CFR) 1910[9] have not been updated.

MANAGEMENT SUPPORT

In compliance with the provisions of Title 29 CFR 1910, management must demonstrate its commitment to personnel safety and health by providing direction and support to an effective safety and health program. Management must clearly state safety guidelines and require that everyone—including management—follow safe practices consistently.

Moreover, in accordance with the provisions originally established in ANSI Z49.1:1967 and NFPA 51B:1962, management[10] must designate approved areas where welding and cutting operations can be performed safely. When welding operations must be performed elsewhere, management must assure that proper safety procedures are established and followed to protect personnel and property.[11]

Management is also responsible for ensuring that only approved welding, cutting, and allied equipment is used in the workplace. This equipment includes torches, regulators, welding machines, electrode holders, and personal protective devices. Management must provide adequate supervision to ensure that all equipment is properly used and maintained.[12]

Contractors hired by management to perform welding operations must employ trained, qualified personnel. Management must inform contractors about any hazardous conditions that may be present in the work area.

HAZARD COMMUNICATIONS

The *Hazard Communication Standard*, 29 CFR 1910.1200,[13] which is included in the *Occupational Safety and Health Act*, requires employers to inform personnel of potential hazards in the workplace and provide training regarding the safe handling of hazardous materials. This standard addresses physical hazards, such as flammability and the potential for explosion, as well as acute and chronic health hazards. The *Hazard Communication Standard* requires that all chemicals produced, imported, or used in U.S. workplaces be evaluated and that hazard information be transmitted to affected employers and exposed employees by means of precautionary information on containers and material safety data sheets (MSDSs) and training.[14]

The *Hazard Communication Standard* identifies many welding consumables as hazardous materials. When welders[15] and other equipment operators are properly taught safe practices, they work more safely and cause fewer accidents. Users must be trained to read and understand all safety documentation before work begins. This documentation includes precautionary information, such as that presented in Figure 17.1, and the manufacturers' safety instructions for the use of materials and equipment, including MSDSs.

Material safety data sheets, which manufacturers, suppliers, and importers are required to provide customers under the *Hazard Communication Standard,* 29 CFR 1910.1200,[16] identify products that could cause health hazards and provide information on each hazardous chemical, including its physical and chemical characteristics, potential effects, and recommendations for protective measures. Material safety data sheets also provide the permissible exposure limit (PEL®) established by OSHA, another exposure limit such as the threshold limit value (TLV®) established by the American Conference of Governmental Industrial Hygienists (ACGIH), or any other limit recommended by the manufacturer.

All employers, including those who use welding consumables, must make applicable material safety data sheets readily available to their employees as well as train them to read and understand their contents. The material safety data sheets used in the welding industry contain important information about the ingredients in welding electrodes, rods, and fluxes; the composition of fumes that may be emitted during use; and means to

8. National Fire Protection Association (NFPA), 1962, *Standard for Fire Prevention in Use of Cutting and Welding Processess,* NFPA 51B:1962, Quincy, Massachusetts: National Fire Protection Association.
9. Occupational Safety and Health Administration (OSHA), 1999, *Occupational Safety and Health Standards for General Industry,* in *Code of Federal Regulations (CFR),* Title 29 CFR 1910, Subpart Q, Washington D.C.: Superintendent of Documents, U.S. Government Printing Office.
10. The term *management* refers to "all persons who are responsible for welding operations such as owners, contractors, and others," as defined in American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 4.
11. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 4.
12. See Reference 11.
13. For more information, see Occupational Safety and Health Administration (OSHA), 1993, *OSHA Fact Sheet 93-26, Hazard Communication Standard, 29 CFR 1910.1200* (available on line at http://www.osha-slc.gov/OshDoc/Fact_data/FSNO93-26.html).
14. See Reference 5.
15. In this chapter, the term *welder* is intended to include all welding and cutting personnel as well as brazers and solderers.
16. See Reference 5.

WARNING:

PROTECT yourself and others. Read and understand this information.

FUMES AND GASES can be hazardous to your health.

ARC RAYS can injure eyes and burn skin.

ELECTRIC SHOCK can KILL.

- Before use, read and understand the manufacturer's instructions, Material Safety Data Sheets (MSDSs), and your employer's safe practices.
- Keep your head out of fumes.
- Use enough ventilation, exhaust at the arc, or both to keep fumes and gases from your breathing zone and the general area.
- Wear correct eye, ear, and body protection.
- Do not touch live electrical parts.
- See American National Standard ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, published by the American Welding Society, 550 N.W. LeJeune Rd., Miami, Florida 33126; and OSHA *Safety and Health Standards*, available from the U.S. Government Printing Office, Superintendent of Documents, P.O. Box 371954, Pittsburgh, PA 15250-7954.

DO NOT REMOVE THIS INFORMATION

Source: Adapted from American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, Figure 1.

Figure 17.1—Minimum Precautionary Information for Arc Welding Processes and Equipment

protect the welder and others from potential hazards. A sample material safety data sheet is presented in Figure 17.2.

TRAINING

As mandated by the provisions of the *Occupational Safety and Health Act,* thorough and effective training is an essential aspect of a safety program. Therefore, in addition to providing access to all applicable government and industry standards, management must ensure that all personnel are properly trained in the safe operation and maintenance of all equipment. For example, personnel must be instructed to position themselves away from gases or fume plumes while performing welding or cutting operations.[17]

Personnel must also be trained to recognize safety hazards in all situations and environments. If they are to work in an unfamiliar situation or environment, they must be thoroughly briefed on the potential hazards involved. For example, welders who work in confined areas that are poorly ventilated must be thoroughly trained in the proper ventilation practices and be cognizant of the adverse consequences of not using them (see the section titled "Confined Spaces" below). Moreover, employees should be trained to question their supervisors before initiating any type of welding or cutting operation if they believe that the safety precautions for a given task are inadequate or misunderstood.

In sum, training must be provided to ensure that all personnel (1) have knowledge of the safety rules that apply for the practices of welding and circumstances they may encounter in the workplace and (2) are familiar with the risks and consequences that may arise should these rules be ignored or violated.

PROTECTION OF THE WORK AREA

Good housekeeping is essential in ensuring safe and healthy working conditions. Welders and supervisors must keep work areas and locations such as passageways, ladders, and stairways clean and clear of obstructions. Since welders shield their vision with necessary eye protection and those passing by a welding station must shield their eyes from the flame or arc radiation, their vision is limited. As eye protection interferes with their vision, welders and passersby can easily trip over objects on the floor. Therefore, management must lay out the production area so that gas hoses, cables, mechanical assemblies, and other pieces of equipment do not cross walkways or interfere with routine tasks.

Safety rails, harnesses, or lines must also be provided to keep workers away from restricted, potentially hazardous areas and prevent falls, whether work is being carried out at floor level or in an elevated location.

17. The term *fume plume* refers to the smoke-like cloud containing minute solid particles that arises directly from the area of melting metal. Unlike gases, fumes are metallic vapors that have condensed to a solid. They are often associated with a chemical reaction such as oxidation.

MATERIAL SAFETY DATA SHEET

(Welding Consumables and Related Products Conforms to the Requirements of OSHA's 29 CFR 1900.1200)

Section 1—IDENTIFICATION	
Manufacturer/Supplier Name	Telephone No.
Address	Date
Trade Name	
Product Type	

Section 2—HAZARDOUS* INGREDIENTS		
IMPORTANT! This section covers the materials from which this product is manufactured. The fumes and gases produced during welding with (normal use of)** this product are covered by Section 3.		
Ingredient***	Approximate Weight %**	Exposure Limit
		Source (1) OSHA (2) ACGIH TLV (3) Mfr. Recommendation

*The term "hazardous" should be interpreted as a term required and defined in the OSHA *Hazard Communication Standard* (29 CFR Part 1910.1200) and does not necessarily imply the existence of any hazard.
**Optional
***Ingredient means the chemical name or common name, chemical abstract service (CAS) registry number (optional), or any other information that reveals precise chemical designation of the substance.

Section 3—PHYSICAL AND CHEMICAL CHARACTERISTICS
Not applicable (*appearance information may be included*).

Section 4—FIRE AND EXPLOSION HAZARD DATA
Nonflammable. Welding arc and sparks, however, can ignite combustibles and flammable products. See guideline reference ANSI Z49.1.

Figure 17.2—Sample Material Safety Data Sheet (MSDS)

Section 5—REACTIVITY DATA
Hazardous Decomposition Products Welding fumes and gases cannot be classified simply. The composition and quality of both are dependent upon the metal being welded and electrodes used. Other conditions which also influence the composition and quantity of the fumes and gases to which workers may be exposed include: coatings on the metal being welded (such as paint, plating, or galvanizing), the number of welders, the volume of the work area, the quality and amount of ventilation, the position of the welder's head with respect to the fume plume, the presence of contaminants in the atmosphere (such as chlorinated hydrocarbon vapors from cleaning and degreasing activities). When the electrode is consumed, the fume and gas decomposition products generated are different in percent and form from the ingredients listed in Section 2. Decomposition products of normal operation include those originating from the volatilization, reaction, or oxidation of the materials shown in Section 2, plus those from the base metal, coatings, etc., as noted above. Reasonably expected fume constituents of this product would include: (insert fume composition). Reasonably expected gaseous constituents of this product would include: (insert gas composition). Ozone and nitrogen oxides may be formed by the radiation from the arc. One recommended way to determine the composition and quantity of fumes and gases to which workers are exposed is to take an air sample inside the welder's helmet if worn or in the worker's breathing zone. See ANSI/AWS F1.1 and ANSI/AWS F1.2.

Section 6—HEALTH HAZARD DATA
Threshold Limit Value: The ACGIH recommended limit for Welding Fume NOC (Not Otherwise Classified) is 5 mg/m^3. ACGIH-1995 (or latest date) preface states "These values are not fine lines between safe and dangerous concentrations and should not be used by anyone untrained in the discipline of industrial hygiene." See Section 5 for specific fume constituents.
Effects of Overexposure Welding may create one or more of the following health hazards: FUMES AND GASES can be dangerous to your health. Short-term (acute) overexposure to welding fumes may result in discomfort such as: metal fume fever, dizziness, nausea, or dryness or irritation of the nose, throat, or eyes and may aggravate pre-existing respiratory conditions, e.g., asthma or emphysema. Long-term (chronic) overexposure to welding fumes can lead to siderosis (iron deposits in the lungs) and may affect pulmonary function. Manganese overexposure can affect the central nervous system resulting in impaired speech and movement. The primary entry route for welding fumes and gases is by inhalation. ARC RAYS can injure eyes and burn skin. ELECTRIC SHOCK can kill. Before use, read and understand the manufacturer's instructions, Material Safety Data Sheets (MSDSs), and your employer's safety practices. Keep your head out of the fumes. Use enough ventilation, exhaust at the arc, or both, to keep fumes and gases from your breathing zone and the general area. Wear correct eye, ear, and body protection. Do no touch live electrical parts.
Emergency and First Aid Procedures Call for medical aid. Employ first aid techniques recommended by the American Red Cross.
Carcinogenicity: NTP? IARC Monographs? OSHA Regulated?

Figure 17.2 (Continued)—Sample Material Safety Data Sheet (MSDS)

Section 7—PRECAUTIONS FOR SAFE HANDLING AND USE/APPLICABLE CONTROL MEASURES
Read and understand the manufacturer's instructions and the precautionary label on the product. See American National Standard Z49.1 (*Safety in Welding, Cutting, and Allied Processes*) and OSHA Publication (29 CFR 1910) for more detail on many of the following.
Ventilation Use enough ventilation, local exhaust at the arc, or both, to keep the fumes and gases from the worker's breathing zone and the general area. Train the welder to keep his head out of the fumes. Keep exposures as low as possible.
Respiratory Protection Use respirable fume respirator or air supplied respirator when welding in confined space or where local exhaust or ventilation does not keep exposure below the recommended exposure limit.
Eye Protection Wear helmet or use face shield with correct shade of filter lens. Provide protective screens and flash goggles, if necessary, to shield others. As a rule of thumb, start with a shade that is too dark to see the weld zone. Then go to the next lighter shade which gives sufficient view of the weld zone.
Protective Clothing Wear hand, head, and body protection which help to prevent injury from radiation, sparks, and electrical shock. See ANSI Z49.1. At a minimum this includes welder's gloves and a protective face shield, and may include arm protectors, aprons, hats, shoulder protection, as well as dark substantial clothing. Train the welder not to touch live electrical parts and to insulate himself from work and ground.
Procedure for Cleanup of Spills or Leaks Waste Disposal Method—Prevent waste from contaminating surrounding environment. Discard any product, residue, disposable container, or liner in an environmentally acceptable manner, in full compliance with federal, state, and local regulations. STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED: not applicable.

Source: Adapted from National Electrical Manufacturers Association (NEMA), 1997, *Guidelines for the Preparation of Material Safety Data Sheets for Welding Consumables and Related Products*, Rosslyn, Virginia: National Electrical Manufacturers Association, Annex.

Figure 17.2 (Continued)—Sample Material Safety Data Sheet (MSDS)

HAZARD NOTIFICATION AND THE POSITIONING OF EQUIPMENT

In accordance with ANSI Z49.1:1999, notification signs should be posted to designate welding areas where eye protection must be worn. Because unexpected events such as fire and explosions can occur in industrial environments, all escape routes must be identified and kept clear to allow for an orderly, rapid, and safe evacuation.[18]

Thus, materials and equipment must not be stored in evacuation routes. Equipment, machines, cables, hoses, and other apparatus should always be situated in such a

18. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, p. 5.

manner so as not to present a hazard to personnel in passageways, on ladders, or on stairways. If an evacuation route must be blocked temporarily, the employees who normally use that route must be informed of the obstructions and trained to use another route to evacuate the premises.

MACHINERY SAFEGUARDING

All personnel must be protected from injuries that may be caused by the machinery and equipment they operate as well as other machinery operating in the work area. Inasmuch as welding helmets and dark filter lenses restrict vision, welders may be more susceptible than other workers to injury from unseen, unguarded machinery. Therefore, moving components and drive belts must be equipped with guards to prevent physical contact. Rotating and automatic welding machines, fixtures, and welding robots must also be outfitted with appropriate guards or sensing devices to prevent operation when personnel are in the hazard area.

During the repair of machinery by means of welding or brazing, the power supply to the machine must be disconnected, locked out,[19] and tagged out[20] to prevent inadvertent operation and injury. Welders assigned to work on equipment whose safety devices are disengaged should fully understand the hazards involved and the steps necessary to avoid accidental injury.

If the pinch points on resistance welding machines, robots, automatic arc welding machines, fixtures, and other mechanical equipment are not properly guarded, they can result in serious injury. To avoid injury with such equipment, a machine should be activated only when the workers' hands are at safe locations. Otherwise, the pinch points must be suitably guarded mechanically. During equipment maintenance, pinch points should be blocked to prevent them from closing in case of equipment failure. In very hazardous situations, an observer should be stationed to prevent the power from being turned on during maintenance.[21]

Metalworking equipment should be carefully safeguarded so as to prevent welders from accidentally falling into or against it while working.

PROTECTIVE BOOTHS

According to the provisions of ANSI Z49.1:1999, workers and others in areas adjacent to welding and cutting areas must be protected from radiant energy and hot spatter by (1) flame-resistant screens or shields or (2) suitable eye and face protection and protective clothing. Appropriate radiation-protective, semitransparent materials are permissible. Operations permitting, workstations should be separated by noncombustible screens or shields. Protective booths with semitransparent shielding are shown in Figure 17.3. Booths and screens should permit air circulation at floor level as well as above the screen.[22]

WALL REFLECTIVITY

In areas where arc welding or cutting is routinely performed, the walls and nearby reflective surfaces must be painted with a finish having low reflectivity of ultraviolet (UV) radiation, such as those formulated with titanium dioxide or zinc oxide.[23] Color pigments may be added providing they do not increase reflectivity. The use of pigments that are based on powdered or flaked metals is not recommended, as these reflect a large amount of UV radiation. As an alternative, welding curtains can be used to minimize reflectivity.[24]

PUBLIC EXHIBITIONS AND DEMONSTRATIONS

Persons conducting exhibits and public demonstrations of arc or oxyfuel gas welding or cutting processes are responsible for the safety of demonstrators and the public. All welding and welding-related equipment used in trade shows and other public events must be installed by or under the supervision of a qualified individual[25]

19. When a piece of machinery is "locked out," a locking device that prevents the switch, valve, or other mechanism from being opened has been installed.
20. When a piece of machinery is "tagged out," a tag reading "DANGER" or "WARNING" along with a short message has been attached to the locking device. The message includes the name and contact information of the person who is responsible for the lock out of the machinery.
21. The topic of the protection of personnel servicing automatic equipment is addressed in Association for Manufacturing Technology (AMT), *Performance Criteria for the Design, Construction, Care, and Operation of Safeguarding When Referenced by the Other B11 Machine Tool Safety Standards,* ANSI B11.19, McLean, Virginia: Association for Manufacturing Technology; and Association for Manufacturing Technology (AMT), *Machine Tools—Manufacturing Systems/Cells—Safety Requirements for Construction, Care, and Use,* ANSI B11.20, McLean, Virginia.
22. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 5–6.
23. For further guidance, see Ullrich, O. A., and R. M. Evans, 1976, *Ultraviolet Reflectance of Paint*, Miami: American Welding Society.
24. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 6.
25. The term *qualified person* denotes "a person who by reason of training, education, and experience is knowledgeable in the operation to be performed and is competent to judge the hazards involved," according to ANSI American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 3.

Figure 17.3—Protective Screens between Workstations

at a site that is located and designed to ensure viewing safety. Electric cables and hoses must be routed away from the audience to avoid possible electric shock or tripping hazards. Exhibitors must also provide protection against fires from fuels, combustibles, and overheated apparatus and wiring. Fire extinguishers must be on hand, and combustible materials must be removed from the area or shielded from flames, sparks, and molten metal.[26]

Appropriate protection for demonstrators, observers, and passersby is mandatory. Overexposure to welding fumes and gases must be controlled by the use appropriate ventilation. Individuals must also be shielded from flames, sparks, molten metal, and harmful radiation. A protective, moveable, transparent screen can be used to permit the audience to observe a welding operation under safe viewing conditions. After welding is completed, the screen can be moved to allow the audience to observe the completed weld.[27]

PERSONAL PROTECTIVE EQUIPMENT

The use of personal protective equipment (PPE) is required by OSHA to reduce the risks of exposure to hazards when administrative measures are not feasible or effective in reducing these risks. Employers are required to identify all potential hazards in the workplace and determine whether PPE should be used to protect workers. Title 29 CFR 1910.132 stipulates that employers must establish general procedures, in the form of a PPE program, to provide employees protective equipment and training in how to use it.[28]

Of particular importance in the welding industry are burns, a serious potential hazard during all welding, brazing, soldering, and cutting operations. Operators and others in the work area must always wear eye, face, hand, foot, and body protection to prevent burns from UV and infrared radiation, sparks, and spatter.

26. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, pp. 18–20.
27. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, pp. 18–19.

28. Occupational Safety and Health Administration (OSHA), 1997, *Assessing the Need for Personal Protective Equipment: A Guide for Small Business Employers*, OSHA 3151 (available on line at http://www.osha-slc.gov/STLC/personalprotectiveequipment).

EYE, FACE, AND HEAD PROTECTION

Protective equipment for the eyes, face, and head must be used by employees who perform tasks that might produce dust, flying particles or molten metal; those who are exposed to extreme heat, physical or chemical irritants, or intense radiation and light such as that created by welding arcs and lasers; and those who may be struck on the head by tools or falling objects.

PPE for the eyes, face, and head includes welding helmets,[29] face shields, welding goggles, and spectacles.[30] Per the specifications of ANSI Z49.1:1, the bodies of welding helmets and shields must be composed of material that is noncombustible, thermally and electrically insulating, and opaque to radiation. The lenses in helmets, shields, and goggles must have protective outer covers to protect the wearer from welding spatter. To protect against flying debris, lift-front helmets must incorporate inner impact-resistant safety lenses or plates.[31]

Filter lenses must be selected in accordance with the ultraviolet, luminous, and infrared transmittance requirements specified in *Practice for Occupational and Educational Eye and Face Protection,* ANSI Z87.1.[32] The shade used must be in accordance with *Lens Shade Selector*, ANSI/AWS F2.2.[33] Table 17.1 presents suggested shade numbers of filter lenses for various welding, brazing, soldering, and thermal cutting processes.

Individuals who have special eye conditions should consult a health care provider for specific information about the use of protective equipment. Contact lens use is permitted, provided lenses are worn in combination with the appropriate safety eyewear, except when the industrial environment presents the probability of exposure to intense heat, significant chemical splash, an extremely particulate atmosphere, or where such use is prohibited by specific regulation.[34]

29. For further information, see American National Standards Institute (ANSI), *American National Standard for Industrial Head Protection,* ANSI Z89.1, Arlington, Virginia: Safety Equipment Association (ISEA).
30. The standards for welding helmets, hand shields, face shields, goggles, and spectacles are specified in American National Standards Institute (ANSI), *Practice for Occupational and Educational Eye and Face Protection*, ANSI Z87.1, Des Plains, Illinois: American Society of Safety Engineers (ASSE).
31. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 8.
32. American National Standards Institute (ANSI), *Practice for Occupational and Educational Eye and Face Protection*, ANSI Z87.1, Des Plains, Illinois: American Society of Safety Engineers (ASSE).
33. American National Standards Institute (ANSI)/American Welding Society (AWS) Committee on Safety and Health. *Lens Shade Selector,* ANSI/AWS F2.2, Miami: American Welding Society.
34. See Reference 3.

Process-Specific Requirements

Specific personal protective equipment requirements for the common welding process are discussed below. These processes include arc welding and cutting, oxyfuel gas welding and cutting, submerged arc welding, torch brazing and soldering, and resistance welding, among others.

Arc Welding and Cutting. To protect against arc rays, sparks, and spatter, welding helmets or hand shields that have appropriate filter lenses and cover plates must be used by welders, welding operators, and nearby personnel when viewing a welding arc. Protective eyewear must also be used during all arc welding and cutting operations. Worn under the welding helmet during arc welding activities, this eyewear must have full, conforming side shields to protect against potentially hazardous rays or the flying particles generated by grinding or chipping operations. Protective eyewear with clear or colored lenses may be used, depending on the intensity of the radiation that personnel may be exposed to from adjacent welding or cutting operations while their welding helmets are raised or removed.[35]

Oxyfuel Gas Welding and Cutting and Submerged Arc Welding. Safety goggles with filter lenses and full, conforming side shields must be worn while performing operations using the oxyfuel gas welding and cutting processes.

During submerged arc welding operations, an arc welding helmet is not needed since the arc is covered by flux and is therefore not readily visible. However, as the arc occasionally flashes through the flux covering the arc zone, the operator should wear safety goggles at all times.

Resistance Welding and Other Processes. Personnel engaged in resistance, induction, salt-bath, dip, and infrared processes must wear safety spectacles and a face shield to protect their eyes and face from spatter. Filter lenses are not necessary but may be used for comfort.

In resistance welding and other processes that may produce sparks and spatter, suitable protection against flying sparks must be provided. Protective devices include shields made of a suitable fire-resistant material or approved personal protective eyewear. However, as resistance welding operations vary, each operation must be evaluated individually with respect to the use of personal protective equipment.

35. American National Standards Institute (ANSI) Accredited Standards Committee Z49, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1, Miami: American Welding Society, p. 6.

Table 17.1
Guide for Shade Numbers

Process	Electrode Size in.	Electrode Size mm	Arc Current (A)	Minimum Protective Shade	Suggested* Shade No. (Comfort)
Shielded metal arc welding (SMAW)	Less than 3/32	2.5	Less than 60	7	—
	3/32–5/32	2.5–4	60–160	8	10
	5/32–1/4	4–6.4	160–250	10	12
	More than 1/4	6.4	250–550	11	14
Gas metal arc and flux cored arc welding (GMAW and FCAW)			Less than 60	7	—
			60–160	10	11
			160–250	10	12
			250–500	10	14
Gas tungsten arc welding (GTAW)			Less than 50	8	10
			50–150	8	12
			150–500	10	14
Air carbon arc cutting (CAC-A)					
Light			Less than 500	10	12
Medium			500–1000	11	14
Plasma arc welding (PAW)			Less than 20	6	6–8
			20–100	8	10
			100–400	10	12
			400–800	11	14
Plasma arc cutting (PAC)					
Light†			Less than 300	8	9
Medium†			300–400	9	12
Heavy†			400–800	10	14
Torch brazing (TB)			—	—	3 or 4
Torch soldering (TS)			—	—	2
Carbon arc welding (CAW)			—	—	14

	Plate Thickness in.	Plate Thickness mm	Suggested* Shade No. (Comfort)
Oxyfuel gas welding (OFW)			
Light	Under 1/8	Under 3.2	4 or 5
Medium	1/8 to 1/2	3.2 to 12.7	5 or 6
Heavy	Over 1/2	Over 12.7	6 or 8
Oxygen cutting (OC)			
Light	Under 1	Under 25	3 or 4
Medium	1 to 6	25 to 150	4 or 5
Heavy	Over 6	Over 150	5 or 6

* As a rule of thumb, the user should start with a protective shade that is too dark to see the weld zone. Then, a lighter shade that provides sufficient visibility of the weld zone without going below the minimum number can be selected. In oxyfuel gas welding or cutting, in which a torch produces a high yellow light, it is desirable to use a filter lens that absorbs the yellow or sodium line in the visible light of the (spectrum) operation.
† These values apply where the arc is clearly seen. Experience has shown that lighter filters may be used when the arc is hidden by the workpiece.

Source: Adapted from American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, Table 1.

Figure 17.4—Typical Protective Clothing for Arc Welding

Torch Brazing and Soldering. Safety spectacles with appropriate filter lenses and with or without side shields are recommended for use during the performance of torch brazing and soldering. As with oxyfuel gas welding and cutting, a bright yellow flame may be visible during torch brazing and soldering. Therefore, filters similar to those used for oxyfuel gas welding and cutting should be used for torch brazing and soldering operations.

HAND, FOOT, AND BODY PROTECTION

Protective gloves, sturdy shoes or boots, and heavy clothing like that shown in Figure 17.4 should be worn to protect the whole body from welding sparks, spatter, and radiation.[36] Hand and arm injuries that may occur in the welding industry include burns, bruises, abrasions, cuts, and chemical exposure. To protect the hands, sturdy, flame-resistant gloves made of leather or other suitable material must always be worn during welding, cutting and related processes. Dry leather gloves in good condition not only protect the hands from burns and abrasion but also provide insulation from welding current electrical shock. Gloves with special linings should be used to protect against high radiant energy.

The specifications for protective footwear are found in the American National Standard *Personal Protection—Protective Footwear*, ANSI Z41.[37] This standard specifies requirements with respect to toe and metatarsal protection, impact and compression resistance, sole puncture resistance, conductivity, and static dissipation.

Body protection shields welding personnel from intense heat; splashes of molten metal; impacts from materials, machinery, and tools; hazardous chemicals; and radiation. Clothing treated with nondurable flame-retardant chemicals must be retreated as recommended by the manufacturer. Welding personnel should avoid wearing any clothing or shoes made of synthetic or plastic materials, which can melt and may cause severe burns. Outer clothing should be kept reasonably free of oil and grease, especially in an oxygen-rich atmosphere. Cuffless pants and covered pockets are recommended to avoid spatter or spark entrapment. Pockets should be emptied of flammable materials, and cuffless pant legs should be worn outside of shoes. A cap providing protection for the hair is recommended. In addition, flammable hair preparations such as hair spray should not be used.[38]

Special protective clothing must be worn by personnel performing overhead welding or when special cir-

36. For further information about this protective gear, refer to American National Standards Institute (ANSI) Accredited Standards Committee Z49, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1, Miami: American Welding Society.

37. American National Standards Institute (ANSI), *Personal Protection—Protective Footwear,* ANSI Z41, Itasca, Illinois: National Safety Council (NSC).

38. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, p. 9.

cumstances warrant additional protection. This clothing includes aprons, leggings, suits, capes, sleeves, and caps, all of which must be made of durable, flame-resistant materials.[39]

HEARING PROTECTION

Hearing loss is one of the leading occupational illnesses in the United States. Occupational exposure to excess noise is a recognized stressor that can affect both behavior and physical well being. Excessive noise, particularly continuous noise at high levels, can cause temporary or permanent full or partial hearing loss as well as hypertension. To protect workers from exposure to excessive noise, OSHA regulates allowable noise exposure levels in *General Industry Standards*, Title 29 CFR 1910.95.[40]

In welding, cutting, and allied operations, noise may be generated by the process or the equipment, or both.[41] Air carbon arc and plasma arc cutting tend to have high noise levels. Engine-driven generators sometimes emit a high noise level, as do some high-frequency and induction welding power sources. Therefore, appropriate noise-limiting devices should be used to protect against possible hearing loss. Properly fitted, flame-resistant earplugs should also be worn when sparks or hot spatter could land in the ears.

RESPIRATORY PROTECTION

In areas where natural or mechanical ventilation is not adequate (see the section titled "Ventilation" below), respiratory protective equipment must be used.[42] When the use of respiratory protection equipment is required by the job, a program must be established to identify and implement the appropriate equipment.

Either dust/mist/fume respirators or any of the new series of respirators approved by National Institute for Occupational Safety and Health (NIOSH) can be used for protection against metal fumes as long as the proper respirator type (e.g., half-mask, full-face, or powered air respiratory protection [PARP]) is selected based on the calculated hazard ratio for the contaminant of concern.[43] A powered air-purifying respirator is shown in Figure 17.5.

Figure 17.5—Powered Air Respiratory Protection

39. See Reference 38.
40. Occupational Safety and Health Administration (OSHA), 1999, *Occupational Safety and Health Standards for General Industry,* in *Code of Federal Regulations (CFR),* Title 29 CFR 1910, Subpart Q. Washington D.C.: Superintendent of Documents, U.S. Government Printing Office.
41. Additional information is presented in American Welding Society (AWS) Committee on Safety and Health, *Arc Welding and Cutting Noise,* Miami: American Welding Society.
42. For additional information, refer to American Welding Society (AWS) Committee on Fumes and Gases, *Methods for Sampling Airborne Particulates Generated by Welding and Allied Processes,* ANSI/AWS F1.1, Miami: American Welding Society.
43. According to National Institute for Occupational Safety and Health (NIOSH), 9 May 2000, Letter to publisher, in July 1995, NIOSH promulgated 42 CFR 84, which modified the requirements for particulate (dust/mist and dust/mist/fume) respirators. The dust/mist and dust/mist/fume classifications were replaced by nine new classes of respirators, categorized as the N-, R-, and P-series. The N-series respirators are not resistant to oils, which can degrade the filter media. The R-series respirators are more resistant to oils, while the P-series are significantly more resistant to oils. Production of the previous series of respirators ceased in July 1998, though distributors were allowed to sell either series until supplies were depleted, and OSHA and the Mine Safety and Health Administration (MSHA) have allowed their use as long as they are available and properly maintained.

Some welding materials (fluxes, welding rods, and residual cleaning and degreasing compounds, for example) may contain harmful materials or release gases and vapors for which filter respirators do not provide adequate protection. In these cases, a chemical cartridge/particulate, gas mask/particulate, or airline respirator should be used. As a general rule, a NIOSH-approved air-supplied respirator should be the only choice as adequate protection when the contaminants themselves or their concentrations have not been identified.[44]

It is also important to note that according to the *Respiratory Protection Standard*, OSHA 29 CFR 1910.134, respirators must not be passed from one worker to another without the equipment's having been sanitized.[45] According to NIOSH, the service life of all filters is limited by considerations of hygiene, damage, and breathing resistance. All filters should be replaced whenever they are damaged or soiled or they cause noticeably increased breathing resistance.[46]

Considering that protection against fumes and gases is essential in the field of welding and its allied processes, this topic is discussed in greater length in the following section.

PROTECTION AGAINST FUMES AND GASES

Many welding and welding-related processes generate gases and fumes that may be harmful. Fumes are composed of air-borne particles of base metal, welding consumables, or coatings that may be present on the workpiece. Welders, welding operators, and all others in the work area must therefore be protected from overexposure to fumes and gases produced during welding, brazing, soldering, and cutting operations. The term *overexposure* is defined as exposure that may pose a health risk and exceeds the permissible limits specified by a government agency such as OSHA in Title 29 CFR 1910.1000 or other recognized authority such as the American Conference of Governmental Industrial Hygienists (ACGIH) in its publication *1999 TLVs® and BEIs®: Threshold Limit Values for Chemical Substances and Physical Agents, Biological Exposure Indices*.[47]

The potential short- and long-term health effects of overexposure to welding fumes and gases can include nausea, headache, dizziness, dermatitis, chronic or acute systemic poisoning, metal fume fever, pneumoconiosis, irritation of the respiratory tract, and possibly cancer.

Proper ventilation (see the section "Ventilation," which follows) usually provides protection against excess exposure. When exposure would exceed permissible limits with the available ventilation, respiratory protection must be used. Fume protection must be provided not only for the welding and cutting personnel but also for others in the area. It is important to note that individuals who have special health problems may have unusual sensitivity that requires even more stringent protection than that specified by a recognized authority.

EXPOSURE FACTORS

Many factors contribute to the amount of fume exposure that may occur during arc welding. The most important factor is the position of the welder's head with respect to the fume plume. When the head is in such a position that the fume envelops the face or helmet, exposure levels can be very high. Thus, welders must be trained to keep their heads to one side of the fume plume. In some cases, the work can be positioned so the fume plume rises to one side.

Welding personnel can also reduce fume exposure by the kind of welding helmet they wear. The extent to which the helmet curves under the chin toward the chest affects the amount of fume exposure. However, it is important to note that the welding helmet alone is not considered an adequate respiratory protection device.

The amount of fume exposure also depends upon the kind of ventilation used. Ventilation may be local, in which case the fumes and gases are extracted near the point of welding, or general, in which case the air from a portion of the shop is changed or filtered. The appropriate type of ventilation to use depends on the welding process, the material being welded, and other shop conditions. Adequate ventilation is necessary to maintain the personnel's exposure to fumes and gases within the recommended limits.

The size of the welding or cutting work area is also important. As a rule, fume exposure inside a tank, pres-

44. National Institute for Occupational Safety and Health (NIOSH), 9 May 2000, Letter to publisher.
45. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 10.
46. National Institute for Occupational Safety and Health (NIOSH), 1997, *NIOSH Respirator User Notice,* in *NIOSH Guide to Selection and Use of Particulate Respirators (Certified under 42 CFR 84,*. U.S. Department of Health and Human Services (DHHS) Publication No. 96-101 (available on-line at http://www.cdc.gov/niosh/userguid.html).

47. American Conference of Governmental Industrial Hygienists (ACGIH), *TLVs® and BEIs®: Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment,* Cincinnati: American Conference of Governmental Industrial Hygienists (also available in Greek, Italian, and Spanish).

sure vessel, or other confined area tends to be higher than that which occurs in a high-bay fabrication area. The size of the work area also affects the background fume level, which depends on the number and type of welding stations, type of ventilation, and the duty cycle for each station.

The type of base metal being welded influences both the constituents and the amount of fume generated. Surface contaminants or coatings may contribute significantly to the potential fume hazards. Paints containing lead and platings containing cadmium emit hazardous fumes during welding and cutting. Galvanized material emits zinc fume.

SOURCES OF FUMES AND GASES

Fumes and gases are usually a greater concern in arc welding than in oxyfuel gas welding, cutting, or brazing. Welding arcs may generate a larger volume of fume and gas, and a greater variety of materials are usually involved in arc welding. Special concerns related to arc welding and cutting, resistance welding, and oxyfuel gas welding and cutting are discussed in the following paragraphs.

Arc Welding and Cutting Fumes and Gases

The fumes and gases produced during arc welding and cutting operations are not simple to classify. Their composition and quantity depend upon a number of factors. These include the welding process employed; the composition of the base metal; the consumables used; the coatings on the workpiece (e.g., paint, galvanizing, or plating); and the contaminants in the atmosphere (e.g., halogenated hydrocarbon vapors resulting from cleaning and degreasing activities); among others.[48]

In welding and cutting, fume is a product of the vaporization, oxidation, and condensation of the components in the consumable and, to some degree, the base metal. The electrode, rather than the base metal, is usually the major source of fume. However, significant fume constituents can originate from the base metal if this contains alloying elements or is covered with a coating that is volatile at elevated temperatures. The composition of the fume usually differs from the composition of the electrode or consumable. The products of the volatilization, reaction, or oxidation of the consumables are reasonably expected fume constituents, as is material from base metals, coatings, and atmospheric contaminants.

Various gases are also generated during welding. Some are a product of the decomposition of fluxes and electrode coatings. Others are formed by the action of arc heat or UV radiation emitted by the arc on atmospheric constituents and contaminants. Still others may come from the external gas shielding that is an inherent part of some welding processes. Potentially hazardous gases include carbon monoxide, oxides of nitrogen, ozone, and phosgene, or other decomposition products of chlorinated hydrocarbons, as well as fluorides. Helium and argon, although chemically inert and nontoxic, can cause asphyxia and dilute the atmospheric oxygen concentration to harmfully low levels. Carbon dioxide and nitrogen can also cause asphyxiation.

Welding arcs, especially gas-shielded arcs using high levels of argon and helium, emit UV radiation. UV radiation can produce ozone from the oxygen in the surrounding air, even at some distance from the UV source. Photochemical reactions between this UV radiation and chlorinated hydrocarbons can result in the production of phosgene and other decomposition products. Welding arcs can also produce carbon monoxide and nitrogen oxides. Arc heat is responsible for the formation of nitrogen oxides from atmospheric nitrogen. Hence, nitrogen oxides may be produced by a welding arc or other high temperature heat sources. Carbon monoxide forms when an arc decomposes carbon dioxide and inorganic carbonate compounds. Levels can be especially significant when carbon dioxide is used as the shielding gas.

The quantity and chemical composition of air contaminants vary substantially from process to process due to the wide range of variables inherent in each process. During arc welding, the arc's energy and temperature depend on the process and the welding variables used in that process. Therefore, fumes and gases are generated in varying degrees in different welding operations.

Consequently, reliable estimates of fume and gas composition cannot be made without considering the nature of the welding process and chemical system being examined. For example, aluminum and titanium are normally arc welded in an atmosphere of argon or helium or a mixture of the two gases. The arc creates relatively little fume but may emit intense UV radiation that can produce ozone. The inert gas shielded arc welding of steels also creates a relatively low fume level.

However, the arc welding of steel in oxidizing environments generates considerable fume and can produce carbon monoxide and oxides of nitrogen. These fumes generally consist of discreet particles of complex oxides containing iron, manganese, silicon, and other metallic constituents, depending on the alloy system involved. Chromium and nickel compounds are found in fumes when stainless steels are arc welded. Some covered and flux cored electrodes are formulated with fluorides. The fumes associated with these electrodes can contain significantly more fluorides than oxides.

48. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 11.

The generation rate of fumes and gases during the arc welding depends on numerous variables, including the following:

1. Welding current,
2. Arc voltage and length,
3. Mode of metal transfer,
4. Shielding gas,
5. Welding process, and
6. Consumables.

These variables are interdependent and can have a substantial effect on total fume generation. They are examined in detail below.

Welding Current. Although fume generation rates generally increase with welding current, the increase varies depending on the process and the type of electrode used. Certain covered, flux-cored, and solid-wire electrodes exhibit a disproportional increase in the fume generation rate with increasing current. Several studies have shown that fume generation rates with covered electrodes are proportional to the welding current raised to a power.[49] For E6010 electrodes, the exponent is 2.24, whereas for E7018 electrodes, it is 1.54.

The relationship between flux-cored and solid-electrode fume generation rates and the welding current is more complex. Welding current levels affect the type of metal droplet transfer. As a result, fume generation rates can decrease with increasing current until a minimum is reached. At this point, fume generation increases in a somewhat proportional fashion.

An increase in current can also increase the emission of UV radiation from the arc. Therefore, the generation of gases formed photochemically by this radiation (e.g., ozone) can be expected to increase as the welding current is increased. Measurements of ozone concentration during gas metal arc and gas tungsten arc welding have shown such behavior.

Arc Voltage and Length. Arc voltage is directly related to arc length. For a given arc length, there is a corresponding arc voltage. The voltage is mostly dependent upon the type of electrode, welding process, and power supply used. In general, increasing the arc voltage (arc length) increases the fume generation rate for all open arc welding processes. The levels of generation differ somewhat for each process and electrode type.

Mode of Metal Transfer. When steel is joined by means of gas metal arc welding using a solid-wire electrode, the resulting mode of metal transfer depends upon the current and voltage used. At a low welding current and voltage, short-circuiting transfer takes place, that is, droplets are deposited during short circuits between the electrode and molten weld pool. As the current and voltage are increased, the mode of metal transfer changes to the globular type, in which large globules of metal are projected across the arc into the weld pool. At high currents and with argon-based shielding, the mode of transfer shifts to spray mode, in which fine metal droplets are serially propelled rapidly across the arc.

The fume generation rate also appears to follow a transition. The fume rate is relatively high during short-circuiting transfer because of arc turbulence. As the transition current is approached in an argon-rich shielding gas, the fume rate decreases and then increases again as spray transfer is achieved. In the spray region, the rate of fume generation is proportional to the welding current.

It has been shown, moreover, that the use of pulsed arc transfer during gas metal arc welding (GMAW-P) results in the generation of significantly less welding fume as compared to conventional gas metal arc welding. This mode of transfer produces a controlled droplet size with a lower average welding current. Thus, the use of this mode can be an effective way of reducing and controlling exposure to welding fume emissions, particularly when implemented in conjunction with local exhaust ventilation that has been properly designed for the application.[50]

For other welding processes, the type of metal transfer varies little with current and voltage. In these cases, fume generation is approximately proportional to the changes in current.

Shielding Gas. Shielding gas must be utilized in gas metal arc welding. It is also required in flux cored arc welding when certain electrodes are used. The type of shielding gas used affects both the composition of the fume and its generation rate. It also affects the kind of gases found in the welding environment. For example, the fume generation rate is higher with carbon dioxide shielding than with argon-rich shielding. The rate of fume formation with argon-oxygen or argon-carbon dioxide mixtures increases with the oxidizing potential of the mixture.

For welding processes in which inert gas shielding is used—gas tungsten arc or plasma arc welding, for example—the fume generation rate varies with the type of gas or gas mixture. More fume can be generated with helium than with argon shielding.

49. American Welding Society (AWS) Committee on Safety and Health, 1979, *Fumes and Gases in the Welding Environment*, Miami: American Welding Society.

50. Wallace, M., D. Landon, A. Echt, and R. Song, 1998, *Control Technology Assessment for the Welding Operations at Vermeer Manufacturing, Pella, Iowa,* Report No. 214-15a, Cincinnati: National Institute for Occupational Safety and Health (NIOSH), Division of Physical Sciences and Engineering.

By-product gases also vary with the composition of the shielding gas. The rate of formation of ozone depends upon the wavelengths and intensity of the UV rays generated in the arc. Ozone is more commonly found with argon-rich gases than with carbon dioxide. Nitrogen oxides are present in the vicinity of any open arc process, and carbon monoxide is commonly found around carbon dioxide-shielded arcs.

Welding Process. Studies conducted on the relative fume generation rates of the consumable electrode processes for welding on mild steel have shown definite trends. Considering the ratio of the weight of fumes generated per weight of metal deposited, covered electrodes and self-shielded flux cored electrodes produce the most fume. Gas shielded flux cored electrodes produce less fume, whereas solid-wire electrodes produce an even lower amount. The submerged arc welding process consistently produces the lowest amount of fumes because the fume is captured in the flux and slag cover.

Consumables. Within a specific process, the fume rate depends upon the composition of the consumables. Some components of covered and flux cored electrodes are designed to decompose and form protective gases during welding. Hence, they generate relatively high fume levels.

Many constituents of covered and flux cored electrodes are proprietary. Therefore, two electrodes with identical AWS classifications may have substantially different fume generation rates because they are produced by two different manufacturers. One way that can be used to compare electrodes is to obtain the material safety data sheet (MSDS) for the product composition to determine specific fume-emission characteristics.

Resistance Welding Fumes and Gases

In resistance welding, fumes and gases as well as airborne particulates can be generated by the materials being welded and the electrodes used. Adequate ventilation must be provided to maintain exposure levels below the allowable limits set by CFR Title 29, Chapter XVII, Part 1910. For more information on resistance welding fumes and gases, the reader is encouraged to consult Section 10 of *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000.[51]

Oxyfuel Gas Welding and Cutting Fumes and Gases

The temperatures encountered in oxyfuel gas welding and cutting are lower than those found in electric arc processes. Consequently, the quantity of fumes emitted is normally lower. The gases formed are the reaction products of fuel-gas combustion and of the chemical reactions between the gases and other materials present. The fumes emitted are the reaction products of the base metals, coatings, filler metals, fluxes, and the gases being used. In the oxyfuel gas cutting of steel, the fumes produced are largely oxides of iron.

Fume constituents that present a greater hazard may be expected when coatings such as galvanizing, paint primers, or cadmium plating are present. The gases of greatest concern include oxides of nitrogen, carbon monoxide, and carbon dioxide. Oxides of nitrogen may be present in especially large amounts during the oxyfuel gas cutting of stainless steels using either the chemical flux or the iron powder process.

VENTILATION

The bulk of fumes emitted during welding and cutting consists of small particles that remain suspended in the atmosphere for a considerable length of time. Thus, the concentration of fume in a closed area can build up over time, as can the concentration of any gas evolved or used in the process. Many particles eventually settle on the walls and floor. However, since fume is produced faster than it settles, fume concentration must be controlled by ventilation.

Adequate ventilation is the key to fume and gas control in the welding environment.[52] Ventilation is adequate when fumes and gases are kept from breathing zones and the general area. Natural, mechanical, or respirator ventilation must be provided for all welding, cutting, brazing, and related operations. The ventilation must ensure that concentrations of hazardous airborne contaminants are maintained below recommended levels. These levels must be no higher than the allowable levels specified by OSHA or other recognized authority.

Welders must always take precautions to keep their breathing zone away from the fume plume even when a sampling of the atmosphere indicates that the concentrations of contaminants do not exceed permissible limits. Air movement should always flow laterally from either side of the welder. Lateral airflow makes it easier for the welder to keep out of the plume and to keep fumes and gases out of the welding helmet. Air should

51. American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society.

52. For additional information, see American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, pp. 10–13.

not blow toward the face or back of the welder because it may force the fume into the breathing zone.[53]

Many ventilation methods are available. They range from natural convection to localized devices, such as air-ventilated welding helmets. Additional ventilation methods include natural ventilation; general area mechanical ventilation; overhead exhaust hoods; portable local exhaust devices; downdraft, crossdraft, and water tables; and extractors built into the welding equipment.

General Ventilation

General ventilation occurs naturally outdoors and indoors when the shop doors and windows are open. In most cases, general ventilation is more effective in safeguarding personnel in adjacent areas than in protecting the welders in the immediate area. According to CFR Title 29 CFR 1910,[54] when all of the following conditions are present, natural ventilation often keeps contaminant concentrations within permissible levels:

1. A work area of more than 10,000 cubic feet (ft^3) (284 cubic meters [m^3]) for each welder is provided;
2. Ceiling height is above 16 ft (5 m);
3. Welding is not performed in a confined area;
4. The general welding area[55] is free of partitions, balconies, or other structural barriers that significantly obstruct cross ventilation; and
5. Toxic materials with low permissible exposure limits are not deliberately present as constituents (the employer should refer to the MSDS).

When natural ventilation is insufficient, fans may be used to force and direct the required amount of air through a building or work room.

The effectiveness of general ventilation, whether natural or forced, is dependent upon the design of the system. Ventilation introducing fresh air and exhausting contaminated air must be arranged in work areas so that the welding fumes and gases are carried away, not concentrated in dead zones. In some cases, the fresh air supply may be located so that incoming fresh air provides the required protection for the welders and personnel in the general area. If this is not possible, general mechanical ventilation may need to supplement local ventilation to keep the background level of airborne contaminants at acceptable levels.

Local Ventilation

Though general ventilation can be used to control contamination levels in the work area, it does not usually provide sufficient local ventilation to protect personnel. Local exhaust ventilation is usually the most effective way of providing protection at workstations. Local ventilation, which provides efficient, economical fume control, can be accomplished with various methods, including the following:

1. Fixed open or enclosing hood,
2. Moveable hood with a flexible duct,
3. Crossdraft or downdraft table,
4. Water table, and
5. Gun-mounted fume removal equipment.

The fixed open or enclosing hood has at least a top and two sides. It must have sufficient airflow and velocity to keep contaminant levels at or below permissible limits.[56] The movable hood, with a flexible duct, is positioned by the welder as close to the point of welding as practicable. This hood should allow sufficient airflow to produce a maximum velocity of 100 ft/min (30 m/min) in the zone of welding. An air velocity of 100 ft/min (31 m/min) will not disturb the torch gas shield during gas shielded arc welding if adequate shielding gas flow rates are used. Higher air velocities may disturb the gas shield and render it less effective. This method of providing local ventilation is shown in Figure 17.6.

Air flow requirements range from 150 ft^3/min (4 m^3/min), when the hood is positioned 4 in. to 6 in. (100 mm to 150 mm) from the weld, to 600 ft^3/min (17 m^3/min) at 10 in. to 12 in. (250 mm to 300 mm) from the weld. These requirements are particularly applicable for bench work but may be used for any location, provided the hood is moved as required.

Another method of achieving local ventilation is the crossdraft or downdraft table. A crossdraft table is a welding bench with the exhaust hood placed to draw air laterally across the table. A downdraft table has a grill as a work surface and an exhaust hood below that draws the air downward and away from the welder's head.

The water table is another technique used to provide local ventilation of the work area. Used for oxyfuel gas and plasma arc cutting operations, this cutting table fills with water to near to the bottom or in contact with the bottom surface of the workpiece. A great deal of

53. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 11.
54. Occupational Safety and Health Administration (OSHA), 1999, *Title 29—Labor,* in *Code of Federal Regulations (CFR,* Chapter XVII, Parts 1901.1 to 1910.1450, Washington D.C.: Superintendent of Documents, U.S. Government Printing Office.
55. In this case, the term *general welding area* refers to a building or a room in a building, not a welding booth or screened area used to provide protection from welding radiation.
56. See Reference 47.

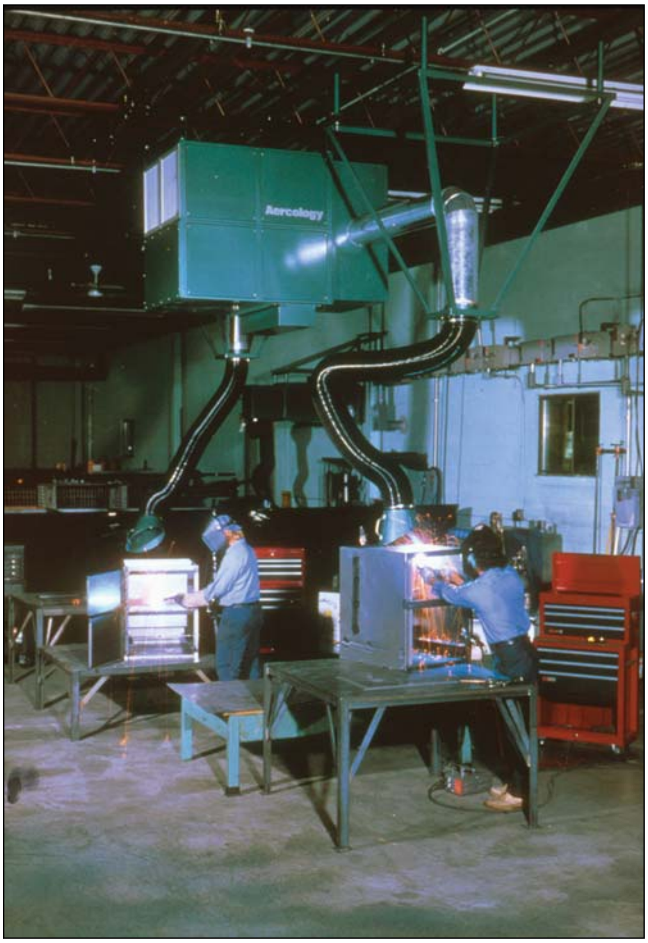

Figure 17.6—Movable Hoods Positioned near the Welding Arcs

Photograph courtesy of Abcor Binzel

Figure 17.7—Fume-Extracting GMAW Torch

the fume that emerges from the cut is captured in the water.

Gun-mounted fume removal equipment, often used with self-shielded flux cored arc welding, extracts the fumes at the point of welding, creating an almost smokeless environment. The exhaust rate must be set so that is does not interfere with the shielding gas pattern provided by the welding process. Virtually all the fume produced by the flux cored arc welding process can be collected using a gun-mounted fume removal device. A fume-extracting torch for gas metal arc welding is shown in Figure 17.7.

Where permissible, air cleaners that can efficiently collect submicron particles may be used to recirculate a portion of ventilated air that would otherwise be exhausted. However, it is important to note that some air cleaners do not remove gases. Therefore, the filtered room air must be monitored to prevent the accumulation of harmful gas concentrations.

SPECIAL VENTILATION SITUATIONS

Some situations are potentially more hazardous than routine welding circumstances. Situations requiring special ventilation include welding in a confined space or welding with certain materials. These are discussed in the following sections.

Welding in Confined Spaces

The terms *confined spaces* and *permit-required confined space* are employed by OSHA to refer to those workspaces that hinder employees' activities while entering, performing operations, or exiting, and those spaces that both hinder employees' activities and pose health or safety hazards, respectively.[57] The American National Standard *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, defines the term as a small or restricted space in which poor ventilation may exist due to the size, or shape of the space.[58] Welding personnel who work in confined spaces are apt to be exposed to serious health and safety hazards, such as asphyxiating or flammable atmospheres. Examples of confined spaces are small rooms, furnaces, ship compartments, reactor vessels, and storage tanks.

57. Occupational Safety and Health Administration (OSHA), 1999, *Confined Spaces* (available on line at http://www.osha-slc.gov/SLTC/confinedspaces).

58. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 2.

Ventilation in confined spaces must ensure sufficient oxygen for life support. In addition, it must keep airborne contaminants at or below the recommended limits in breathing atmospheres and prevent the accumulation of flammable mixtures.[59] Inasmuch as ventilation must also prevent the occurrence of oxygen-enriched atmospheres, oxygen levels should remain between 19.5% and 23.5% per volume (natural air contains approximately 21% oxygen by volume). Only clean, respirable air must be used for ventilation; the use of pure oxygen, other gases, or mixtures of gases for ventilation purposes is prohibited.[60]

Without an adequate supply of the proper concentration of oxygen, welders may asphyxiate, become unconscious, and possibly die without apparent warning symptoms. It should be noted that in confined areas, oxygen-enriched atmospheres—especially those with more than 25% oxygen—also pose other hazards. Materials that burn normally in air may flare up violently in such atmospheres. Therefore, clothing may burn fiercely; oil- or grease-soaked clothing or rags may catch fire spontaneously; and paper may flare into flame, all of which may cause severe or even fatal burns.

Confined areas must be tested for toxic or flammable gases and vapors and adequate oxygen supply prior to entry and during occupancy. The tests should be conducted with instruments approved by the U.S. Mine Safety and Health Administration (MSHA). It is also advisable that a continuous monitoring system with audible alarms be used. It is important to note that these same safety precautions apply to other areas as well. Gases that are heavier than air—argon, methylacetylene-propadiene (MPS), propane, and carbon dioxide, for example—might accumulate in pits, tank bottoms, low areas, and near floors. Gases that are lighter than air—helium and hydrogen, for example—may accumulate in tank tops, high areas, and near ceilings.[61]

If proper ventilation cannot be ensured, personnel lacking the proper training and personal protective equipment must never enter the confined work area. The welders, cutters, and other personnel who do work in such areas must wear an approved positive-pressure air-supplied breathing apparatus that is self-contained.[62] They must also have an emergency air supply lasting at least five minutes in the event that the main air source fails. Another person wearing similar safety equipment should also be present. When work is carried out in confined areas in atmospheres that are immediately hazardous to life and health, attendants knowledgeable in rescue procedures must be stationed outside of the area. Each attendant must have his or her own self-contained breathing device.[63]

Besides testing atmospheric conditions, workers in confined space must take additional precautions. Because compressed gas cylinders could leak gases or volatiles, they must be located outside confined areas. Welding power sources must also be placed outside of any confined space to reduce the hazard of electric shock and asphyxiation from engine exhaust. Personnel must be able to exit quickly in the event of an emergency. Those using safety belts and lifelines must ensure that this equipment is worn properly so that it does not become entangled or jammed while they are attempting to exit.[64]

The operation of brazing furnaces also poses potential hazards. These furnaces, which are a type of confined space, utilize a variety of atmospheres (a vacuum, inert gas, flammable gas, or flammable gas combustion products, for example) to exclude oxygen. Thus, among the hazards presented are the accumulation of hazardous fumes or gases in the work area, the development of explosive mixtures of flammable gas and air, and the asphyxiation of personnel.[65]

Welding of Containers and Piping

The welding or cutting of containers and vessels also presents special risks.[66] Fires, explosions, and health hazards can result if the objects contain combustible, reactive, or toxic materials. Thus, the precautions for confined spaces must be observed. All containers should be considered unsafe for welding and cutting unless

59. For further precautions, see American National Standards Institute (ANSI), *Safety Requirements for Confined Spaces,* ANSI Z117.1, Des Plains, Illinois: American Society of Safety Engineers (ASSE).
60. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 16–17.
61. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 16.
62. Air-supplied respirators and hose masks must be approved by the U.S. Mine Safety and Health Administration (MSHA) or other recognized agency.
63. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 17–18.
64. See Reference 63.
65. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 18.
66. Per American Welding Society (AWS) Committee on Labeling and Safe Practices, 1994, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping,* ANSI/AWS F4.1-94, Miami: American Welding Society, the following types of containers require specialized safety considerations: containers that can be entered by personnel; containers that have held radioactive substances; containers that have held compressed gases; containers that have held explosive substances; ship tanks, bunkers, or compartments; gasometers or gas holders for natural and manufactured gases; outside, above-ground vertical petroleum storage tanks; containers holding flammable substances that must be repaired while in service (p. 1). For safe practices specific to these container types, the reader is advised to consult the latest edition of this standard and any other applicable regulatory and industry-specific codes and guidelines.

they are judged clean or rendered safe by a qualified person. Additionally, the immediate area outside and inside the container should be cleared of all obstacles and hazardous materials.[67] When repairing a container in place, the welder must never allow hazardous substances released from the floor or the soil beneath the container to enter. The required personal and fire protection equipment must also be available, serviceable, and in position for immediate use.

One method used to weld containers safely involves filling the container with an inert medium such as water, gas, or sand. When using water, the level should be kept to within a few inches from the welding point. The space above the water should be vented to allow the heated air to escape. When employing inert gas, the responsible individual must know how to produce and maintain a safe atmosphere during welding, including the percentage of inert gas required in the tank to prevent fire or explosion.

Gases generated during welding must be discharged safely and in an environmentally friendly manner in accordance with government rules and regulations. This is especially important when welding inside containers, where workers must prevent pressure buildup. When needed, testing for gases, fume, and vapors should be conducted periodically to ensure that recommended limits are maintained during welding.

Low-Allowable-Limit Materials

Certain materials sometimes present in consumables, base metals, coatings, or atmospheres for welding, cutting, or brazing operations have permissible exposure limits at or below those specified by the authority having jurisdiction. These constituents include antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, mercury, nickel, selenium, silver, and vanadium.[68] Table 17.2 presents the base and filler metals that may release some of these materials in fume during welding, cutting, and allied operations.

The manufacturer's MSDSs, which should be supplied, can be consulted to determine if any of these materials are present in the welding filler metals and fluxes being used. It is best to remember, however, that hazardous materials may also be present in base metals, coatings, or other sources in the work area. Radioactive materials under the jurisdiction of the Nuclear Regulatory Commission (NRC) require special consideration.

When any of these materials is encountered as a designated constituent in welding, brazing, or cutting operations, special precautions must be taken to ensure that atmospheric contaminants remain at or below permissible levels for human exposure. Unless atmospheric tests under the most adverse conditions establish that exposure is within acceptable concentrations, certain precautions are necessary—both indoors and outdoors. Whenever any materials with a low allowable limit are encountered in indoor operations, local exhaust mechanical ventilation must be used. When beryllium is encountered indoors, respiratory protection in addition to local exhaust ventilation is essential. In confined spaces, local exhaust ventilation and respiratory protection must be used, and all personnel in adjacent areas must be similarly protected.[69]

Additionally, personnel must refrain from consuming food in areas where fumes contain materials with very low allowable exposure limits. To prevent the ingestion of these contaminants, welding personnel should also practice good personal hygiene, such as washing their hands before touching food.

Table 17.2
Possible Hazardous Materials
Emitted during Welding or Thermal Cutting

Base or Filler Metal	Emitted Metals or Their Compounds
Carbon and low-alloy steels	Chromium, manganese, vanadium
Stainless steels	Chromium, manganese, nickel
Manganese steels and hard-facing materials	Chromium, cobalt, manganese, nickel, vanadium
High copper alloys	Beryllium, chromium, copper, lead, nickel
Coated or plated steel or copper	Cadmium*, chromium, copper, lead, nickel, silver

*When cadmium is a constituent in a filler metal, a precautionary label must be affixed to the container or coil. Refer to Section 9 of American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, 20–22.

67. Refer to American Welding Society (AWS) Committee on Labeling and Safe Practices, 1994, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping*, ANSI/AWS F4.1-94, Miami: American Welding Society and to Occupational Safety and Health Administration (OSHA), 1999, *Title 29—Labor,* in *Code of Federal Regulations (CFR),* Chapter XVII, Parts 1901.1 to 1910.1450, Washington D.C.: Superintendent of Documents, U.S. Government Printing Office.

68. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 12.

69. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 12–13.

Fluorine and Zinc Compounds

The inhalation of the fumes and gases from fluorine compounds can be hazardous. These compounds can also burn the eyes and skin on contact. Thus, local mechanical ventilation or respiratory protection must be provided when welding, brazing, cutting, or soldering operations in confined areas involve fluxes, coatings, or other material containing fluorine compounds.

In open spaces, the need for local exhaust ventilation or respiratory protection against fluorine compounds depends upon the circumstances. Local exhaust ventilation is not necessary when air samples taken in breathing zones indicate that all fluorides are within allowable limits. However, local exhaust ventilation is always desirable when fluorine compounds are used in fixed-location or stainless-steel production welding.

Zinc compounds, which may be present in consumables, base metals, or coatings, can produce nausea, dizziness, or metal fume fever (sometimes referred to as *Galo fever*). Therefore, the same safety procedures for fumes containing fluorine compounds also apply to fumes containing zinc compounds.

Cleaning Compounds

Inasmuch as cleaning compounds may be hazardous or flammable, they often require special ventilation precautions. The manufacturer's instructions should be carefully followed before welding or cutting on cleaned materials.[70]

Chlorinated Hydrocarbons

Degreasing or cleaning involving chlorinated hydrocarbons must be carried out in an area where the vapors from these operations are prevented from entering the atmosphere in the vicinity of the molten weld metal or the welding arc. When these vapors enter the atmospheres of arc welding operations, a reaction produces highly toxic phosgene gas, which has an irritating, objectionable odor. Low levels of exposure can cause nausea, dizziness, and weakness, whereas high exposure levels can cause serious health impairment or even death.[71]

Cutting of Stainless Steel

As stainless steel contains chromium and nickel compounds, the fume emitted during cutting operations may be hazardous. Symptoms of overexposure to fumes containing these compounds may include headaches, nausea, and dizziness. Therefore, when cutting stainless steel using oxyfuel gas, gas shielded arc, or plasma arc cutting, local mechanical ventilation should be implemented to remove the fumes emitted. In underwater plasma arc cutting, the water captures most of the fume.

AIR SAMPLING AND MEASUREMENT OF EXPOSURE

When ventilation is questionable, the only manner in which to ensure that airborne contaminant levels are within the allowable limits is to take air samples of the breathing zone. When an operator's actual on-the-job exposure to welding fume and gases is to be sampled, the guidelines provided in *Methods for Sampling Airborne Particulates Generated by Welding and Allied Processes,* ANSI/AWS F1.1,[72] must be adhered to. This document describes the techniques used to obtain an accurate breathing zone sample of welding fume for a particular welding operation. Both the amount and composition of the fume can be determined in a single test using the method described. Multiple samples are recommended for increased accuracy, one of which must be collected inside the welder's helmet, if one is worn.

The American Conference of Governmental Industrial Hygienists (ACGIH) and OSHA have established allowable limits of airborne contaminants, referred to as *threshold limit values* (TLV) or *permissible exposure limits* (PEL), respectively. The TLV is the concentration of an airborne substance to which most workers may be repeatedly exposed, day after day, without adverse effect. The threshold limit value-time weighted average (TLV-TWA) is used to adapt threshold limit values to normal workplace conditions. The TLV-TWA is the time-weighted average airborne substance concentration to which nearly all personnel may be repeatedly exposed without adverse effect during a normal eight-hour workday or 40-hour workweek. TLV-TWA values should be used as a general guide for controlling health hazards, not as a sharp, clear division between safe and hazardous concentrations of airborne substances. Revised annually, the TLVs may or may not correspond to OSHA's permissible exposure limits for the same materials. In many cases, current ACGIH values for welding materials are more stringent than OSHA levels.

70. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 13.
71. See Reference 70.

72. American Welding Society (AWS) Committee on Fumes and Gases, *Methods for Sampling Airborne Particulates Generated by Welding and Allied Processes,* ANSI/AWS F1.1, Miami: American Welding Society.

SAFE HANDLING OF COMPRESSED GASES

The gases used in welding and cutting operations are packaged in containers that are referred to as *cylinders*.[73] The gas cylinders utilized in welding operations contain gas that is pressurized at approximately 2500 pounds per square inch gauge (psig) (17 237 kilopascal [kPa]) or higher. Gases at these pressures must be handled properly to prevent damage to the cylinders. Mishandling may result in leaks or explosions, causing damage, injury, or death.[74]

Only cylinders constructed and maintained in accordance with U.S. Department of Transportation (DOT) specifications can be used in the United States. The use of other cylinders is illegal and may be extremely hazardous. Cylinders requiring periodic retest under DOT regulations may not be filled unless the retest is current.[75]

FILLING CYLINDERS AND MIXING GASES

According to the provisions of ANSI Z49.1:1999[76] and *Safe Handling of Compressed Gas in Containers*, CGA P-1-1999,[77] cylinders may be filled only by the owner or individual authorized by the owner. Mixing gases and filling one cylinder from another are hazardous; therefore, the mixing and transfilling should not be attempted by anyone who is not qualified and authorized to perform this activity. Combustible or incompatible combinations of gases must never be mixed in cylinders.[78]

LABELING

Before using gas from a cylinder, welding personnel must carefully read the label, which provides the chemical or trade name of the contents in accordance with regulations. The label is the only proper notice of the cylinder's contents. Other means of marking—including cylinder color, banding, or shape—must not be used as they may vary among manufacturers, geographical areas, or product lines and could be misleading. If the label is illegible or no label is affixed to the cylinder, the contents must not be used and the cylinder must be returned to the supplier.[79]

STORAGE AND USAGE

Gas cylinders and other containers must be stored in accordance with all state and local regulations and the appropriate standards issued by OSHA and the Compressed Gas Association (CGA). Safe handling and storage procedures are discussed in detail in the CGA's *Handbook of Compressed Gases*[80] and *Safe Handling of Gas in Containers,* CGA P-1.[81]

Numerous precautions must be taken in the use and storage of gas cylinders. Cylinders must be stored in areas where they are protected against tampering and exposure to extreme temperatures. Storage temperatures must not fall below –20°F (–30°C) or exceed 125°F (52°C). They must also be stored at an adequate distance from welding activities to prevent exposure to slag, sparks, or flames; alternatively, fire-resistant shields must be used. The rough handling of gas cylinders should be avoided; therefore, cylinders must be protected from bumps, falls, falling objects, and weather and must never be dropped. In addition, cylinders must be stored away from passageways, elevators, or stairs where they might be struck, knocked over, or damaged by vehicles.

Cylinders containing acetylene and liquefied gas must always be stored and used in the upright position. Other cylinders are preferably stored and used in the upright position. Moreover, cylinders must always be secured to prevent them from falling during storage and use. During transport by motor vehicle, they must be secured according to U.S. DOT regulations. During lifting, they must be hoisted using the proper cradle or platform, not electromagnets or slings. Any of these exposures, misuses, or abuses could cause damage to cylinders and severe consequences.[82]

73. For additional information on safe practices in the handling of compressed gases, refer to Compressed Gas Association (CGA), 1999, *Handbook of Compressed Gases,* 4th ed. Boston: Kluwer Academic, or the latest edition.
74. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 26.
75. For further information, see Compressed Gas Association (CGA), *Safe Handling of Gas in Containers*, CGA P-1, Arlington, Virginia: Compressed Gas Association.
76. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society.
77. Compressed Gas Association (CGA), 1999, *Safe Handling of Gas in Containers*, CGA P-1:1999, Arlington, Virginia: Compressed Gas Association.
78. See Reference 74.
79. See Reference 74.
80. Compressed Gas Association (CGA), 1999, *Handbook of Compressed Gases,* 4th ed. Boston: Kluwer Academic, or the latest edition.
81. Compressed Gas Association (CGA), *Safe Handling of Gas in Containers*, CGA P-1, Arlington, Virginia: Compressed Gas Association.
82. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 6–27; Compressed Gas Association (CGA), 1999, *Safe Handling of Gas in Containers*, CGA P-1-1999, Arlington, Virginia: Compressed Gas Association.

Due to the inherent risks of fire and explosion, gas cylinders must never be welded. Cylinders must never be used as work rests or rollers. Moreover, they must not be allowed to become part of an electrical circuit because arcing may result. Cylinders containing the shielding gases used in conjunction with arc welding must not be placed where they might become part of an electrical circuit. To prevent arcing or interference with valve operation, items such as electrode holders, welding torches, cables, hoses, or tools must not be stored on gas cylinders. Arc-damaged gas cylinders may leak or rupture, thereby injuring and possibly killing anyone nearby.[83]

Many cylinders have a valve protection cap to protect the cylinder valve. This cap should always be in place except when the cylinder is in use. The cylinder should never be lifted by the valve protection cap because the threads that secure these protection caps may not be capable of supporting the full weight of the cylinder. The caps should always be threaded completely onto the cylinders and hand-tightened.

Gas Withdrawal

Many gases in high-pressure cylinders are filled to pressures of 2000 psig (13 790 kPa) or more. Unless the equipment to be used with a gas is designed to operate at full-cylinder pressure, an approved regulator must be used to reduce pressure by withdrawing gas from a cylinder or manifold. Simple needle valves should never be used. A pressure-relief or safety valve that is rated to function at less than the maximum allowable pressure of the welding equipment should also be employed as a backup in case the regulator fails. The valve is designed to prevent equipment failure at pressures in excess of working limits. The equipment involved in the withdrawal of gas from cylinders is discussed in more detail below.

Cylinder Valves

Valves on cylinders containing high-pressure gas, particularly oxygen, must always be opened slowly. If the valves are opened too rapidly, the high temperature associated with adiabatic recompression can occur. In the case of oxygen, the heat can ignite the valve seat, which, in turn, may cause the metal to melt or burn. To avoid injury, welding personnel must open the cylinder valve outlet while standing to one side of the outlet, not in front of it.

Before a gas cylinder can be connected to a pressure regulator or a manifold, the valve outlet must be cleaned of dirt, moisture, and other foreign matter by wiping it with a clean, oil-free cloth. Then, in order to prevent dirt or dust from entering the regulator, the valve is opened for an instant and closed immediately—a procedure known as *cracking* the cylinder valve. Fuel gas cylinders must never be cracked near sources of ignition (i.e., sparks and flames), in confined spaces, or while operators are smoking. In addition, before a regulator is connected to a gas cylinder, the regulator must be drained of gas pressure. After shutting down the operation, the cylinder valve must be closed.[84]

The outlet threads on cylinder valves are standardized for specific gases so that only regulators or manifolds with similar threads can be attached.[85] Preferably, the valves on low-pressure fuel gas cylinders should be opened using no more than one turn. This usually provides adequate flow and allows the valve to be closed quickly in the event of an emergency. In contrast, high-pressure cylinder valves must usually be opened fully to backseat the packing and prevent packing leaks during use.

The cylinder valve should be closed after each cylinder use and when returning an empty cylinder to the supplier. This prevents hazardous gas leaks that might develop and remain undetected while the cylinder is unattended. It also prevents the back flow of contaminants into the cylinder. It is advisable to return cylinders to the supplier with approximately 25 psi (172 kPa) of contents remaining. This practice prevents possible contamination of the cylinder by the atmosphere during shipment.

Pressure-Relief Devices

Pressure-relief devices are intended to protect cylinders that are subjected to a hostile environment, such as fire or other source of heat that may raise the pressure within the cylinders. These safety mechanisms are designed to relieve the pressure in gas cylinders to within safe limits. Only trained personnel are allowed to adjust cylinder pressure-relief devices. The available types of pressure-relief devices, their maintenance, and application are addressed in *Pressure-Relief Device Standards—Part I: Cylinders for Compressed Gases*, CGA S-1.1.[86]

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83. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 29.

84. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 28.

85. Refer to Compressed Gas Association (CGA), *Compressed Gas Cylinder Valve Outlet and Inlet Connections*, 7th ed., ANSI/CGA V-1, Arlington, Virginia: Compressed Gas Association.

86. Compressed Gas Association (CGA), *Pressure-Relief Device Standards—Part I: Cylinders for Compressed Gases*, CGA S-1.1, Arlington, Virginia: Compressed Gas Association.

Regulators

A pressure-reducing regulator must always be used when withdrawing gas from cylinders for use in welding or cutting operations. All gas regulators must meet the requirements specified in *Standard for Gas Pressure Regulators*, CGA E-4,[87] and other code regulations.

Pressure-reducing regulators must be used only for the gas and pressure specified on the label affixed to the cylinder although the cylinder's valve outlet threads may be the same as those on other gas cylinders. Threaded connections should never be forced onto the regulator. An improper fit between the gas cylinder and the regulator or between the regulator and hose constitutes an improper—and unsafe—combination of devices. Before a cylinder is used, all threads and the regulator's connection glands must be inspected for dirt or damage. If a hose or cylinder connection leaks, the connection must not be forced with excessive torque. Damaged regulators and components must be repaired by properly trained mechanics or returned to the manufacturer for repair.

A suitable valve or flowmeter should be used to control gas flow from a regulator. The regulator's internal pressure must be drained before the regulator is connected or removed from a gas cylinder or manifold. An adapter must not be used to change the cylinder connection, as this increases the risk of using an inappropriate or contaminated regulator. For instance, gases that are contaminated with oil can deposit an oily film on the internal parts of the regulator. This film can contaminate oil-free gas or, in the case of oxygen, can cause fire or explosion. Further details are specified in CGA's *Standard Connections for Regulator Outlets, Torches, and Fitted Hose for Welding and Cutting Equipment*, CGA E-1.[88]

Manifold Piping Systems

A manifold is used when gas is needed without interruption or at a higher delivery rate than can be supplied from a single cylinder. A manifold and its components must be leak-tight and designed for a specific gas and operating pressure. The components of the manifold must be used for the gas and pressure for which they are approved only. Oxygen and fuel gas manifolds must meet additional specific design and safety requirements.[89]

Manifold piping systems must incorporate an appropriate overpressure relief valve unless the system is specifically designed and constructed to withstand full cylinder or tank pressure. A pressure-relief device should be sufficient to prevent the overpressurization of the system's weakest element. To be effective, a pressure-relief device such as a relief valve or bursting disc must be isolated from other protective devices (such as another relief valve) and located in every section of the system that might be exposed to the full force of the supply pressure. However, welding personnel should beware of relying solely on pressure-reducing regulators. Some pressure regulators have integral safety-relief valves designed for the protection of the regulator only. These alone should not be relied upon to protect the downstream system, however.

In cryogenic piping systems, relief devices must be located in every section of the system that could trap liquefied gas. Upon warming, such liquids vaporize to gas, and in a confined area, gas pressure can increase dramatically. Pressure-relief devices protecting fuel-gas piping systems or other hazardous gas systems must vent gas in safe locations. Piping and fittings for manifolds carrying acetylene or methylacetylene-propadiene (MPS) must not consist of any unalloyed copper or alloys containing 70% or more copper. Acetylene and MPS react with copper under certain conditions to form unstable copper acetylide, a compound that may detonate under shock or heat.

In addition, each fuel gas cylinder lead should incorporate a back flow check valve and a flash arrester. Back flow check valves should also be installed in each line at each station outlet where both fuel gas and oxygen are provided for a welding, cutting, or preheating torch. Back flow check valves must be examined periodically for tightness per the manufacturer's instructions.[90]

OXYGEN

Though oxygen is nonflammable, it vigorously accelerates combustion in flammable materials. Therefore, oxygen cylinders and liquid-oxygen containers must be stored away from combustibles and fuel-gas cylinders. Oil, grease, and combustible dusts may spontaneously ignite on contact with pure oxygen. Hence, all manifold systems and apparatus manufactured expressly for oxygen service must be kept free of any combustibles. Oxygen valves, regulators, and apparatus must never be lubricated with oil. If lubrication is required, the type of lubricant and the method of applying the lubricant should be specified in the manufacturer's literature. If these indications are not specified, the device should be

87. Compressed Gas Association (CGA), *Standard for Gas Pressure Regulators*, CGA E-4, Arlington, Virginia: Compressed Gas Association.
88. Compressed Gas Association (CGA), *Standard Connections for Regulator Outlets, Torches, and Fitted Hose for Welding and Cutting Equipment*, CGA E-1, Arlington, Virginia: Compressed Gas Association.
89. For additional information on manifold and piping systems, refer to National Fire Prevention Association (NFPA), *Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processes,* NFPA 51, Quincy, Massachusetts: National Fire Prevention Association.

90. Compressed Gas Association (CGA), 1998, *Hose Line Flashback Arrestors,* Technical Bulletin TB-3, Arlington, Virginia: Compressed Gas Association.

returned to the manufacturer or authorized representative for service. Valves, piping, or system components not expressly manufactured for oxygen service must be cleaned and approved for oxygen service before use in an operation.[91]

It is also important to note the difference between pure oxygen and air. Pure oxygen supports combustion much more vigorously than air, which contains only 21% oxygen. Thus, pure oxygen should never be used as a substitute for compressed air; otherwise, raging fires and explosions may occur. For example, pure oxygen must never be used to power compressed air tools, which are typically lubricated with oil. Similarly, pure oxygen must never be used to blow dirt from workpieces and clothing, which are also often contaminated with oil, grease, or combustible dust. Only clean clothing should be worn when working with oxygen systems. In addition, pure oxygen must never be used to ventilate confined areas. This would create an oxygen-rich atmosphere that could be ignited by a chemical reaction or separate ignition energy in conjunction with a fuel.

Information regarding special procedures for oxygen cylinders is provided in Section 10 of ANSI Z49.1:1999.[92] Additional information is available in *Oxygen*, CGA G-4,[93] and *Torch Standard for Welding and Cutting,* CGA E-5.[94]

FUEL GAS

Fuel gases commonly used in oxyfuel gas welding and cutting are acetylene, methylacetylene-propadiene (MPS), natural gas, propane, and propylene. Hydrogen is also used in a few applications. Gasoline, which vaporizes in the torch, is sometimes used as a fuel for oxygen cutting. These gases should always be referred to by name, not by the generic term "gas." The rate of withdrawal of fuel gases from cylinders must never surpass that recommended by the manufacturer.[95]

Acetylene and MPS require special precautions. Acetylene possesses the lowest explosive limit of all the fuel gases. When acetylene is stored in cylinders, it is dissolved in a solvent so that it can be safely maintained under pressure. In the free state, acetylene must never be used at pressures higher than 15 psig (103 kPa) because it can decompose with explosive violence. Moreover, neither acetylene nor MPS should be used in contact with silver, mercury, or alloys containing 70% or more copper. These gases react with these metals to form unstable compounds that may detonate under shock or heat. For this reason, the valves on fuel gas cylinders must never be opened to clean the valve outlet near possible sources of flame ignition or in confined areas.[96]

Hydrogen also requires special attention. Hydrogen flames may be difficult to see or invisible. Because of this lack of visibility, the torch and flame should be handled with extreme care as the body, clothes, or combustibles may easily be exposed to hydrogen flames.

Fuel gases used for brazing furnace atmospheres must be burned or vented to a safe location. Before filling a furnace or retort with fuel gas, the equipment must first be purged with a nonflammable gas, such as nitrogen or argon, to prevent the formation of an air-fuel mixture that could explode.

Preventing Fuel-Gas Fires

Fuel-gas systems can cause fire hazards. Most fuel gases in cylinders are in liquid form or dissolved in liquids. Therefore, gas cylinders should always be used in the upright position to prevent liquid surges into the system.

One source of fire in welding and cutting is the ignition of leaking fuel by sparks or spatter. The best procedure for avoiding fire from a fuel gas or liquid is to prevent leaks in the manifold system. All fuel systems should be checked carefully for leaks upon assembly and at frequent intervals thereafter. Fuel-gas cylinders should frequently be examined for leaks, especially at fuse plugs, safety devices, and valve packing.

If a leak is discovered around the valve of a fuel gas cylinder, the packing nut must be tightened or the valve must be closed.[97] If the fuel leak cannot be stopped, the cylinder should be removed by trained fire personnel to a safe location outdoors. The supplier should also be notified. A warning sign should be posted, and no smoking or other sources of ignition should be permitted in the area. In case of fire, the fire alarm should be activated, and trained fire personnel should be summoned immediately.

One of the most effective means of controlling a fuel fire is to shut off the fuel valve, if accessible. A fuel gas

91. Refer to Compressed Gas Association (CGA), *Cleaning Equipment for Oxygen Service,* G4.1, Arlington, Virginia: Compressed Gas Association.
92. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 23–31.
93. Compressed Gas Association (CGA), *Oxygen,* G-4, Arlington, Virginia: Compressed Gas Association.
94. Compressed Gas Association (CGA), *Torch Standard for Welding and Cutting,* CGA E-5, Arlington, Virginia: Compressed Gas Association.
95. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 30.
96. For additional information on acetylene, see Compressed Gas Association (CGA), *Acetylene*, CGA G-1, Arlington, Virginia: Compressed Gas Association.
97. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 30.

valve should never be opened beyond the point necessary to provide adequate flow, which is usually no more than one turn of the handle. This practice makes it possible for the valve to be shut off quickly in an emergency. If the immediate valve controlling the burning gas is inaccessible, another upstream valve may cut off the flow of gas.

A small fire near a cylinder's safety device or valve can be controlled using water, wet cloths, or fire extinguishers. If a large fire at a fuel gas cylinder occurs, the fire alarm should be sounded, and all personnel should be evacuated from the area. The cylinder should be kept wet and cool by fire personnel with a heavy stream of water. It is usually better to allow the fire to continue to burn and consume all issuing gas rather than attempt to extinguish the flame. Otherwise, although the flames have been extinguished, the escaping gas may re-ignite with explosive violence.[98]

SHIELDING GAS

Argon, helium, nitrogen, and carbon dioxide and their mixtures in cylinders and manifold systems are used for shielding with some welding processes. All of these, except carbon dioxide, are used as brazing atmospheres. These gases are odorless and colorless, and they can displace the air needed for breathing. For this reason, confined areas filled with these gases must be well ventilated before personnel are permitted to enter.

Should there be any question regarding the presence of these gases in a work area, the area must be monitored for adequate oxygen concentration with an oxygen analyzer. If an analyzer is not available, air-supplied respirators must be worn by personnel entering the area. In addition, containers filled with these gases must not be placed in confined spaces, as pointed out previously (see the section "Welding of Containers").

CRYOGENIC LIQUIDS

Cryogenic cylinders and tanks are used to store at very low temperatures those liquids that evaporate at room temperature. The cryogenic liquids used for commercial purposes include oxygen, nitrogen, and argon, though other gases may also be handled like cryogenic liquids. The cylinders and tanks utilized for storing cryogenic liquids are usually double-walled. They are evacuated and insulated between the walls. Designed to keep temperatures low and minimize heat increase, these liquid-gas containers hold a greater amount of gas for a given volume than high-pressure gas cylinders.

For safety, these containers must be handled carefully. They must always be maintained in an upright position and transported only in cylinder-handling trucks specifically designed for the transport of these containers. In addition, they must not be rolled on a bottom edge, as is often done with high-pressure cylinders. Overpressurization could cause an explosion.

If these cylinders are handled improperly, the inner or outer cylinder wall can rupture, causing a loss of vacuum and a rapid rise of internal pressure. When this occurs, the cylinder's protective devices are designed to activate, allowing the contents to escape. These cylinder protection devices must never be tampered with.

A visible frosting on the container's exterior is a sign of damage to the internal walls or fittings. Whenever this frosting appears, the gas supplier must be notified, and personnel should keep clear until the frost disappears. Generally, when the frost disappears, the contents have evaporated and any internal pressure has been relieved.

Cryogenic liquid, which is a gas at room temperature, evaporates before exiting the cylinder by passing through a vaporizer system, warming the gas to atmospheric temperature. In some cases, however, the user may want to withdraw the contents in liquid form. Should this extremely cold liquid contact the skin, it may cause burns similar to those caused by hot substances. Contact with the liquid can also result in severe frostbite. Therefore, to prevent bodily contact from these cold liquids, users must wear protective clothing. An adequate face shield and loose-fitting insulated gloves that can be quickly removed in case of an exposure emergency and are essential.

The properties of many materials at room temperature change drastically at cryogenic liquid temperatures. Many metals, including carbon steel, and most elastomers, such as rubber, become extremely brittle. When cryogenic liquids are to be withdrawn from cylinders, the transfer line must be made of materials that maintain satisfactory properties at these low temperatures.

It is also important to note that liquid oxygen may react with explosive violence on contact with asphalt or similar bituminous materials. Thus, liquid oxygen must not be allowed to come into contact with these materials. Liquid-oxygen tanks must always be installed on concrete pads—never on asphalt or similar bituminous materials.

Further information on this topic is provided in *Safe Handling of Cryogenic Liquids,* P-12,[99] *Safe Handling of Liquefied Nitrogen and Argon,* CGA AV-5,[100] and

98. See Reference 97.

99. Compressed Gas Association (CGA), *Safe Handling of Cryogenic Liquids,* P-12, Arlington, Virginia: Compressed Gas Association.

100. Compressed Gas Association (CGA), *Safe Handling of Liquefied Nitrogen and Argon,* CGA AV-5, Arlington, Virginia: Compressed Gas Association.

Standard for Cryogenic Liquid Transfer Connections, CGA V-6.[101]

PROTECTION AGAINST ELECTROMAGNETIC RADIATION

Electromagnetic fields, ultraviolet radiation, and infrared radiation are produced by most arc welding and cutting processes as well as by electron beam welding; laser beam welding; and torch welding, cutting, brazing, or soldering. Although radiation is invisible, it can inflict injury. The most common injuries resulting from exposure to radiation are skin burns and eye damage.

Two types of radiation—ionizing and nonionizing—can be produced during welding operations. Ionizing radiation, produced by electron beam welding, can be maintained within acceptable levels with shielding around the welding area. During the grinding of thoriated tungsten electrodes for gas tungsten arc welding, a local exhaust system must be used to prevent the inhalation of the dust, which is radioactive. Respiratory protection should also be used, if necessary. Otherwise, users should follow the instructions on the manufacturer's material safety data sheet (MSDS) for the thoriated tungsten electrode. Protection against nonionizing radiation includes the use of safety glasses with UV protective side shields in addition to a welding helmet with the correct filter plate. In addition, the skin must be protected with adequate hand and body personal protective equipment, as specified by ANSI Z49.1:1999.[102, 103]

ELECTRICAL SAFETY

Most welding and cutting operations employ some type of electrical equipment. For example, even oxyfuel gas cutting machines use motor drives, controls, and various other electrical systems. In the absence of precautionary measures, personnel may be injured or even killed by electric shock in welding and cutting operations. Some electrical accidents, such as those caused by lightning, are unavoidable; however, the majority can be avoided with the proper training and safety precautions.

A good safety training program in electrical safety is essential. Before working with any electrical application, employees must be fully instructed in electrical safety by a competent professional. As a minimum, this training should include the points covered in Part II of ANSI Z49.1:1999.[104]

Electric shock occurs when an electric current of sufficient magnitude passes through the body. The severity of the shock depends primarily on the amount of current, the duration and path of flow, and the individual's state of health. The amount of current depends upon the applied voltage, which causes the current to flow, and the resistance of the body path. The frequency of the current may also be a factor when alternating current (ac) is involved.

Currents greater than about 5 milliamperes (mA) are considered primary shock currents because they are capable of causing direct physiological harm. Steady-state currents less than 5 mA are considered secondary shock currents, which are capable of causing involuntary muscular reactions without normally causing direct physiological harm. Most people begin to feel a tingle from the current at 0.5 mA; therefore, this point is referred to as the *perception threshold.*

SOURCES OF ELECTRIC SHOCK

Electric shock can originate from natural sources or from equipment. Shock from natural sources is exemplified by that caused by lightning-induced voltage surges in power distribution systems. Even earth grounds can attain high potential relative to true ground during severe transient phenomena due to power line faults or lightening strikes, though such circumstances are rare. Most electrical equipment can present a hazard of shock if improperly installed, used, or maintained. Thus, for purposes of safety, all equipment must be installed, operated, maintained, and repaired by qualified personnel. Worn, damaged, or inappropriate cables must not be used.

In welding and cutting activities, most electrical equipment is powered from ac sources of 115 volts (V) to 575 V or by engine-driven generators. Most welding operations require less than 100 V. Some arc cutting methods use power sources that operate at more than 400 V, while electron beam welding machines operate at up to approximately 150 kilovolts (kV). These levels warrant precautions because fatalities can result even with equipment that operates at less than 80 V.

In the welding industry, most instances of electric shock occur because of accidental contact with bare or

101. Compressed Gas Association (CGA), *Standard for Cryogenic Liquid Transfer Connections,* CGA V-6, Arlington, Virginia: Compressed Gas Association.
102. See Reference 76.
103. See Reference 3.
104. See Reference 76.

poorly insulated conductors. Therefore, welders must take precautions against contacting bare elements in the welding circuit and primary circuits.

When performing welding operations in electrically hazardous conditions, personnel must take special care to prevent electric shock. Examples of electrically hazardous conditions are (1) wet or damp areas, (2) restricted work areas that force personnel to work in an uncomfortable position, making contact with conductive parts, and (3) areas in which contact with conductive elements is likely.[105]

Water or moisture typically reduces electrical resistance, often creating more severe electrical hazards. When arc welding or cutting in damp or wet conditions—including conditions creating heavy perspiration—welding personnel must wear dry, nonconductive gloves and clothing in good condition to prevent electrical shock. Welders should also be protected from electrically conductive surfaces, including the earth, by means of rubber-soled shoes or an insulating layer such as a rubber mat or dry wooden board, which is preferred. Under such hazardous conditions, welders can also employ a semiautomatic direct-current (dc) power source, a dc manual shielded metal arc power source, or an arc welding power source with reduced voltage control. The use of these power sources can reduce the possibility of electric shock.

When welders are required to work in a cramped kneeling, sitting, or lying position, they should implement the same precautions discussed above. The hazards posed by making contact with conductive elements can be minimized by insulating the parts in the operator's vicinity.[106]

As a general safety precaution, rings and other jewelry should be removed before welding to decrease the possibility of electric shock.

EQUIPMENT SELECTION

In addition to the use of proper clothing and body protection, operators can reduce the possibility of electric shock by selecting and using the proper equipment. Operators should use the correct equipment designed for each job and situation. All equipment must meet the applicable standards, such as *Transformer-Type Arc Welding Machines,* UL 551,[107] and other standards issued by the National Electrical Manufacturers Association (NEMA) such as *Electric Arc Welding Power Sources*, ANSI/NEMA EW 1.[108]

As previously mentioned, if a significant amount of welding and cutting work is performed under electrically hazardous conditions, the use of automatic machine controls that reduce the no-load (open-circuit) voltage to a safe level is recommended. When special welding and cutting processes require open-circuit voltages higher than those specified in ANSI/NEMA EW 1,[109] adequate insulation and operating procedures must be provided to protect personnel from these higher voltages.

INSTALLATION

Personnel installing electrical equipment must follow the requirements of the National Fire Protection Association's (NFPA) *National Electric Code (NEC)®*, ANSI/NFPA 70,[110] and other local codes. These codes describe necessary disconnects, fusing, and the different types of incoming power lines, among other topics. All electrical equipment should be installed in an area that is clean and dry. If installation in a clean dry area is not possible, the equipment should be adequately safeguarded from dirt and moisture.

Terminals for welding leads and power cables must be shielded from accidental contact with personnel or metal objects, such as vehicles and cranes. Connections between welding leads and power supplies may be guarded utilizing (1) dead-front construction using receptacles for plug connections, (2) terminals located in a recessed opening or under a nonremovable hinged cover, (3) insulating sleeves, or (4) other equivalent mechanical means.[111]

GROUNDING

The workpiece and the frame or chassis of all electrically powered machines must be placed or connected to a good electrical ground, such as a grounded metal floor or platen. They can also be connected to a properly grounded building frame or other satisfactory ground. Special radio-frequency grounding may also be

105. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 31.
106. See Reference 105.
107. Underwriters Laboratories (UL), *Transformer-Type Arc Welding Machines,* UL 551, Northbrook, Illinois: Underwriters Laboratories.
108. National Electrical Manufacturers Association (NEMA), *Electric Arc Welding Power Sources,* EW 1, Rosslyn, Virginia: National Electrical Manufacturers Association.
109. See Reference 108.
110. National Fire Protection Association (NFPA), *National Electric Code (NEC)®*, ANSI/NFPA 70, Quincy, Massachusetts: National Fire Protection Association.
111. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 32.

necessary for arc welding machines equipped with high-frequency arc initiating devices and arc stabilizers.[112] Chains, wire ropes, cranes, hoists, and elevators must never be used as grounding connectors or as carriers of welding current.[113]

It is important to note that the work lead is not the grounding lead. The work lead connects the work terminal on the power source to the workpiece. A separate lead is required to ground the workpiece or power source work terminal. Thus, great take care must be taken when connecting the grounding circuit to avoid double grounding. Otherwise, the welding current may flow through a connection intended only for grounding, and the welding current may be of higher magnitude than the grounding conductor can carry safely.

Portable control devices such as push buttons must not be connected to circuits having operating voltages above approximately 120 V. Exposed metal parts on portable control devices operating on circuits above 50 V must be grounded by a grounding conductor in the control cable. Controls using intrinsically safe voltages below 30 V are recommended.

CONNECTIONS AND CABLES

Electrical connections must be tight and clean to prevent local heating; therefore, they must be checked periodically. Magnetic work clamps must be free of an accumulation of metal particles and spatter on contact surfaces. Coiled welding leads should be spread out before use to avoid overheating and damage to the insulation. When jobs alternately require long and short leads, insulated cable connectors should be used so that the idle lengths can be disconnected when they are not needed.[114]

Equipment, cables, fuses, plugs, and receptacles must be used within their current-carrying and duty-cycle capacities. The operation of apparatus above the current rating or the duty cycle causes overheating and the rapid deterioration of insulation and other parts. When welding with short leads or low voltages, or both, the actual welding current may be higher than that shown by the indicators on the welding machine. General purpose welding machines are likely to render high currents when they are used with processes that use low arc voltage, such as gas tungsten arc welding.

Welding lead cable should be flexible and designed especially for the rigors of welding service. The insulation on cables used with high voltages or high-frequency oscillators must provide adequate protection. The cable manufacturer's recommendations and precautions must be followed. Cable insulation must be maintained in good condition, and cables must be repaired or replaced promptly when necessary.

OPERATION

To ensure overall safe operation, welding personnel must be knowledgeable of the codes and standards related to their responsibilities. Personnel must have access to written rules governing the safe operation of equipment. These rules must be strictly followed.[115]

Welders must not allow the energized metal parts of electrodes, electrode holders, or torches to touch their bare skin or any wet apparel. Electrode holders must not be cooled by immersion in water, and electrode-holder insulation must be kept in good condition. Before using water-cooled welding guns or holders, welders must inspect them for any water leaks and condensation, which would compromise safety. In addition, welders must not drape or coil the welding leads around their bodies.[116]

During operation and work interruptions, welding circuits must be de-energized to avoid electric shock while the electrode, torch, or gun is being changed or adjusted. The only exception is shielded metal arc welding, during which the welding circuit need not be de-energized while electrodes are changed. However, when the circuit is energized in shielded metal arc welding, covered electrodes must be changed with dry welding gloves, never with bare hands. De-energizing a circuit is always desirable for optimum safety, even with covered electrodes.[117]

At the end of an operation or when leaving the workstation for an appreciable time, operators must turn a welding machine off. Similarly, when the machine is to be moved, the input power supply must be disconnected at the source. When equipment is not in use, exposed electrodes must be removed from the holder to eliminate the hazard of accidental electrical contact with workers or conducting objects. Semiautomatic welding guns must be placed so that the gun switch cannot be operated accidentally.[118]

112. See Section 10.5.6 in National Electrical Manufacturers Association (NEMA), 1988, *Electric Arc Welding Power Sources,* EW 1–1988. Rosslyn, Virginia: National Electrical Manufacturers Association.
113. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 33–34.
114. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 35.
115. See Reference 114.
116. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 36–37.
117. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 36.
118. See Reference 114.

MODIFICATION AND MAINTENANCE

Defective electrical equipment or safety hazards must be reported to the supervisor as soon as these are identified. Faulty equipment must not be used until it has been serviced by authorized personnel and its safety has been assured. Only qualified personnel are permitted to modify and maintain electrical equipment. Welding machines require numerous modification and maintenance procedures. Typical procedures are listed below:[119]

1. Commutators on rotating welding machines must be kept clean to prevent excessive arcing;
2. Rectifier welding machines must be inspected frequently for accumulations of dust or lint that might interfere with ventilation;
3. Louvers and internal electrical coil ventilating ducts require inspection for the accumulation of dust and lint;
4. Welding machines may be blown out occasionally with clean, dry, compressed air at low pressure unless prohibited by the manufacturer. Adequate safety precautions, such as the proper eye protection, must be observed;
5. The use of air filters in the ventilating systems of electrical components is not recommended unless these are provided by the welding machine's manufacturer. If used, filters should be inspected as recommended by the manufacturer as the reduction of air flow from dust accumulating on the air filter can cause internal components to overheat and fail altogether;
6. Machines that have become wet must be thoroughly dried and properly retested before being operated;
7. All input connections must be checked; and
8. All grounding connections must be verified.

MULTIPLE-ARC WELDING OPERATIONS

Increased hazard of electrical shock exists when several welders are working on a large metal structure, such as a building frame or ship, that is part of the return welding circuits. Proper electrical contact must exist at all joints in the structure. Sparking or heating at any point in the structure renders it unsuitable as a return circuit.

When two or more welders working on the same structure are likely to touch the exposed parts of more than one electrode holder simultaneously, the welding machines must be connected to minimize the hazard of shock. Ideally, all dc welding machines should be connected with the same polarity. A test lamp or voltmeter can be used to determine whether the polarities are matched. It is also preferable to connect all single-phase ac welding machines to the same phase of the supply circuit with the same instantaneous polarity. These precautions minimize the potential difference in polarity between electrode holders.

In some cases, the preferable connections may not be available. Welding may require both dc polarities, or supply circuit limitations may necessitate the distribution of ac welding machines among the phases of the supply circuit. In these cases, the no-load voltage between electrode holders or welding guns may be twice the normal voltage. Because of the increased voltage, the welders and other personnel in the area must be instructed to avoid simultaneous contact with more than one electrode holder, welding gun, or installed electrode.[120]

SPECIAL PRECAUTIONS FOR PACEMAKER WEARERS

Inasmuch as pacemakers are electrical in operation, their functioning may be compromised by the presence of the strong electromagnetic fields produced by electric arc welding and cutting. Therefore, the wearers of pacemakers or other electronic equipment vital to life must consult a physician and the manufacturer regarding possible hazards before performing these operations.

Pacemaker wearers who have been cleared to perform welding and cutting activities must observe special precautions. Welding current settings higher than necessary should not be used by pacemaker wearers. Welding cables should be kept close together and positioned to one side of the welder. Repeated, short spurts of welding should be avoided; 10 seconds should be allowed to transpire between welds. Pacemaker wearers should not work alone and must stop welding and seek immediate medical attention if they feel ill.[121]

FIRE PREVENTION AND PROTECTION

Most precautions against electrical shock are also applicable to the prevention of electrical equipment fires, which may be caused by overheating electrical components, sparks, or spatter from welding or cutting

119. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 37.

120. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 34.

121. See Reference 3.

operations, or the mishandling of fuel in overheated engine-driven equipment. For engine-driven equipment, fuel systems must be in good condition. Otherwise, the ignition system, electrical controls, spark-producing components, or engine heat may start a fire. Leaks must be repaired promptly. Engine-driven machines must be turned off before refueling, and any fuel spills should be wiped up and fumes allowed to dissipate before the engine is restarted.

In most welding, cutting, and allied processes, a high-temperature heat source is present. Open flames, electric arcs, molten metal, sparks, and spatter are ready sources of ignition. Sparks and spatter can pass through or lodge in cracks, holes, and other small openings in floors and walls, often causing fires. As sparks can travel up to 35 ft (10.7 m) from their source and fall much greater distances, floors must always be free of combustible materials for a radius of at least 35 ft (10.7 m) around the work area.[122]

Without the proper protective shields, welding or cutting too close to combustibles increases the risk of fire. The materials most commonly ignited are combustible floors, roofs, partitions, and building contents including trash, wood, paper, textiles, plastics, chemicals, and flammable liquids and gases. Outdoors, the most common combustibles are dry grass and brush.

The best protection against fire is to perform welding and cutting away from combustibles in specially designated areas or noncombustible enclosures. Combustibles should always be removed from the work area. Combustibles that cannot be removed from the area, including combustible walls, ceilings, doorways, windows, cracks and other openings, should be covered with tight-fitting flame-resistant material. Alternatively, the work area itself can be enclosed with portable flame-resistant screens. Combustible floors must be protected with damp sand, sheet metal, or water. If water is used, measures must be taken to protect personnel from experiencing electric shock. Appropriate fire-extinguishing equipment must be available for immediate use in the work area.[123]

Personnel should refrain from welding or cutting in atmospheres that contain hazardously reactive or flammable gases, liquids, vapor, or dust. Moreover, heat should not be applied to a container that has held an unidentified substance or combustible material or to a workpiece covered with an unidentified substance or flammable coating.[124]

The fuel for engine-driven equipment must be carefully stored and handled. The equipment manufacturer's instructions should be followed because the fuels and vapors commonly found in welding and cutting areas are combustible and can be explosive under some conditions. Examples of such fuel gases are acetylene and propane. All fuel-gas cylinders, hoses, and apparatus must be carefully inspected for leaks. Welders must also be alert for the traveling vapors of flammable liquids. Vapors are often heavier than air and can travel along floors and in depressions for a considerable distance from the location where the flammable liquid is stored. In addition, light vapors can travel along ceilings to adjacent rooms.

When welding or cutting material on or adjacent to a metal wall, ceiling, or partition, heat that is conducted through the metal can ignite combustibles on the opposite side. Therefore, combustibles on the other side of the barrier must be moved to a safe location. If this cannot be accomplished, a fire watcher (see below) must be stationed to monitor the combustibles.

Welding, brazing, or cutting must not be performed on any material having a combustible coating or internal structure. This is the case with certain walls, ceilings, floors, and platforms. Moreover, hot scrap or slag must not be placed in containers holding combustible materials. After the operation has been completed, the work area should be inspected for fires for at least 30 minutes. Personnel should be alert for conditions that may warrant an extension of this period. Supervisory personnel should also inspect the area before leaving.

FIRE WATCHERS

According to the provisions of ANSI Z49.1:1999[125] and *Fire Prevention during Welding, Cutting, and Other Hot Work*, NFPA 51B,[126] fire watchers—qualified personnel who are trained in fire detection, the fire reporting process, and emergency rescue procedures—must be situated in areas where welding or cutting operations are being performed and where a fire might start. Fire watchers must also be posted when any of the following are present:

1. Combustibles within 35 ft (10.7 m) of welding or cutting operations;
2. Wall or floor openings that expose combustible materials within a radius of 35 ft (10.7 m);
3. Metal walls, ceilings, roofs, or pipes adjacent to which materials that are likely to ignite by means of radiation or conduction are located; and

122. See Reference 3.
123. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, p. 14.
124. See Reference 3.
125. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, p. 15.
126. National Fire Protection Association (NFPA), 1999, *Fire Prevention during Welding, Cutting, and Other Hot Work*, NFPA 51B, Quincy, Massachusetts: National Fire Protection Association.

4. Ship work that poses a fire hazard to an adjacent compartment.

Fire watchers are allowed to perform additional duties providing these do not distract them from detecting fires.

HOT-WORK AUTHORIZATION

When welding, cutting, or similar hot-work[127] operations are to be performed in an area not designated for these activities, the hot-work authorization system is used to alert area supervisors to the extraordinary hazard of fire. The authorization, which is usually written, should incorporate a checklist of safety precautions, including an inspection of fire extinguishers; the establishment of fire watches, if necessary; a search for flammable materials; and safety instructions for area personnel who are not involved in the hot work.[128]

EXPLOSION PREVENTION

When certain gases, vapors, and dusts are mixed with oxygen or other elements in certain proportions, they can cause explosions and fires. The heat, sparks, and spatter produced during welding and related activities may cause otherwise low-volatile materials to produce flammable vapors. All of these materials must be kept in leak-tight containers or be well removed from the work area.

Welding, brazing, soldering, or cutting activities should never be carried out in an atmosphere containing flammable material. Personnel must also refrain from placing any operating equipment that can produce heat or sparks near these flammables. Inasmuch as some welding operations involve the risk of explosion, personnel must always wear proper personal protective equipment (PPE).

Containers must be vented before applying heat. Heat must not be applied to a container that has held an unknown material, a combustible substance, or a substance that may form flammable vapors upon the application of heat.[129] The container must first be thoroughly cleaned or filled with an inert gas. In addition, heat should never be applied to a workpiece covered by an unknown substance or to a substance that may form flammable or toxic vapors when heated.

PROCESS-SPECIFIC SAFETY CONSIDERATIONS

Broad safety guidelines for most welding, cutting, brazing, or soldering processes have been addressed above. The precautions and procedures unique to particular processes are discussed in this section. All applicable precautions and guidelines discussed below must be considered as part of a safety program in the workplace.

OXYFUEL GAS WELDING AND CUTTING

Acetylene, methylacetylene-propadiene (MPS), natural gas, propane, propylene, and hydrogen are commonly used in oxyfuel gas welding and cutting. In addition, gasoline is sometimes used as a fuel for oxygen cutting. As mentioned above, these fuels should always be referred to by name, not by the generic term "gas."

Oxygen Equipment

Oxygen equipment—including cylinders and pipelines—must not be used interchangeably with any other gas. Failure to comply with this measure may result in spontaneous combustion or explosion as a result of the contamination of the oxygen apparatus with combustible substances.[130]

Torches

Only welding and cutting torches that have been approved by the authority with jurisdiction must be used in oxyfuel gas welding and cutting operations. Oxyfuel gas torches must meet appropriate government regulations and the requirements stipulated in *Torch*

127. The term *hot work* is defined as "any work involving burning, welding, or similar operations capable of initiating fires or explosions" in American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 15.

128. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 15.

129. Additional information is provided in American Welding Society (AWS) Committee on Labeling and Safe Practices, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping,* ANSI/AWS F4.1, Miami: American Welding Society.

130. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 23.

Standard for Welding and Cutting, CGA E-5.[131] Torches should be kept in good working order and serviced at regular intervals by the manufacturer or qualified technicians. A torch must be used only with the fuel gas for which it was designed. The fuel gas and oxygen pressures should be those recommended by the torch manufacturer. Torches must be inspected for leaking before lighting, and frequent leak testing should be performed when the equipment has been employed in such a way as to induce leaks.[132]

To minimize the hazard of burns on the hands and fingers, the manufacturer's recommendations must be followed when lighting and extinguishing the torch. The torch should be lighted only with a friction lighter, pilot light, or similar ignition source. Matches, cigarette lighters, or welding arcs must never be used as a source of ignition. The manufacturer's specifications must also be followed regarding the sequencing of operations while lighting, adjusting, and putting out torch flames.[133]

Hoses

Only those hoses that have been specified for use in oxyfuel gas welding and cutting systems may be used. Hoses used in oxyfuel gas service must be manufactured in accordance with the standard *Specifications for Rubber Welding Hose,* ANSI/RMA IP-7.[134] Hoses must be in good condition and free of oil and grease. Worn, leaking, defective hoses must be repaired or replaced. In the United States, red hose with left-hand threaded fittings is typically used for fuel gas, while green hose with right-hand threaded fittings is used for oxygen.[135] To permit color recognition and ensure adequate ventilation, when parallel lengths of hose are strapped together, no more than 4 in. (100 mm) of any 12 in. (300 mm) section of hose should be taped. The hose colors used internationally are specified in *Welding—Rubber Hoses for Welding, Cutting, and Allied Processes,* ISO 3821.[136, 137]

Only the proper ferrules and clamps should be used to secure hose to fittings. Long runs of hose should be avoided. Excess hose should be coiled to prevent kinks and tangles, but it should not be wrapped around cylinders or cylinder carts while in use.

Backfire and Flashback

The term *backfire* refers to the momentary retrogression of the flame back into the torch tip, causing the tip flame to disappear and then reappear. This is accompanied by a pop or bang, depending upon the size of the tip. In severe cases, the hot combustion products within the tip may be forced back into the torch and even the hoses. Backfires occasionally ignite the inner liner of the hose and result in burn-through of the hose wall, especially when using oxygen. Such backfires can result in injury. In addition, when the hose ruptures, the gases flow out of the tube into the atmosphere until the valve at the tank is closed.

The term *flashback* describes a phenomenon that is usually characterized by a whistling or squealing sound. Flashback is initiated by a backfire in which the flame continues to burn inside the equipment instead of being re-established at the tip. This causes a very rapid internal heating that can easily destroy the equipment. This rapid heating may also cause sparks to issue from the tip. Flashback should be extinguished by turning off the torch valves as quickly as possible. Different manufacturers recommend shutting off either the fuel or oxygen first, but the most important concern is to shut both valves quickly.

Backfires and flashbacks are not ordinarily a concern when the manufacturer's instructions have been followed. When they do occur, the operator allowed the tip to become overheated by flame backwash, forcing the tip into the work, or providing insufficient gas flow for the size of the tip. If frequent backfires or flashbacks occur, the work should be stopped, and the equipment or operation should be investigated.

To prevent backfires and flashbacks, hose lines should always be purged before oxyfuel gas equipment is lighted. Purging flushes out any combustible oxygen-fuel or air-fuel gas mixtures in the hoses. Hoses are purged by opening either the fuel or the oxygen valve on the torch and allowing the gas to flow for several seconds to clear the hose of any possible gas mixtures. That valve is then closed, and the other valve is opened to allow the other gas to flow for a similar period. The purge stream must not be directed toward any flame or other source of ignition. Torches must not be purged in confined areas because accumulated, highly concentrated gas may explode.

Hose-Line Safety Devices

When they are installed and operating properly on hose lines, reverse-flow check valves and flashback arres-

131. See Reference 94.
132. See Reference 130.
133. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 24.
134. Rubber Manufacturers Association (RMA), *Specifications for Rubber Welding Hose,* ANSI/RMA IP-7, Washington, D.C.: Rubber Manufacturers Association.
135. Hose connections must comply with requirements stipulated in Compressed Gas Association (CGA), *Standard Connections for Regulator Outlets, Torches, and Fitted Hose for Welding and Cutting Equipment*, CGA E-1, Arlington, Virginia: Compressed Gas Association.
136. International Organization for Standardization (ISO), *Welding—Rubber Hoses for Welding, Cutting, and Allied Processes,* ISO 3821, Geneva: International Organization for Standardization.
137. See Reference 133.

tors can prevent the reverse flow of gases and flashbacks into hoses. These safety devices must be used, inspected, and maintained strictly in accordance with the manufacturer's instructions and recommendations.[138]

Regulators

Pressure-reducing regulators must be approved according to the specifications of *Standard for Gas Pressure Regulators,* CGA E-4.[139] These regulators must be used for the gases and pressures specified on their labels only. Inlet connections must be made in accordance with *Compressed Gas Cylinder Valve Outlet and Inlet Connections,* ANSI/CGA V-1,[140] and all connections must be inspected for leak-tight performance before use. Regulators must not be used interchangeably among designated gas applications. In order to minimize the possibility of fire, oxygen regulators must be drained of gas before they are connected to a manifold or a cylinder, and valves must always be opened slowly.[141]

Shutdown Procedures

When oxyfuel gas operations are finished, the equipment must always be completely shut down, with the gas pressures drained from the system and all cylinder supply valves closed. The equipment must not be left unattended until the shutdown has been completed.

Ventilated Storage

Oxyfuel gas cylinders or equipment connected to cylinders must always be stored in well-ventilated areas, rather than in confined areas, such as unventilated cabinets. Even small gas leaks in confined areas can create mixtures that might cause disastrous explosions. For the same reason, gas cylinders should never be transported in enclosed vehicles, particularly in closed vans or the trunks of automobiles.

ARC WELDING AND CUTTING

The potential hazards of arc welding and cutting, discussed in detail above, necessitate precautions that must be followed. Potential hazards encountered in arc welding and cutting include electric shock, asphyxiation, fumes and gas, infrared and UV radiation, burns, fire, explosion, and noise. Noise levels during arc cutting operations can be very high, and prolonged exposure can cause hearing impairment. A certified safety specialist or industrial hygienist can be consulted to measure occupational exposure levels in the work area and make recommendations. Whenever necessary, approved ear protection, such as ear plugs or muffs, must be provided for operators and others in the area.

Plasma arc cutting is a particularly noisy process and one that also emits a great deal of fume. Two common accessories can be used in the mechanized plasma arc cutting of plate to aid in fume and noise control. One method is the water table, discussed above (see the section titled "Local Ventilation"). This is a cutting table filled with water to the bottom surface of the plate or above the plate. In the latter case, cutting is done under water using a special torch to minimize noise and reduce radiation. The high-speed gases emerging from the plasma jet produce turbulence in the water, consequently trapping most fume particles in the water.

Another accessory designed to reduce noise is the water muffler, a nozzle attached to a special torch body that produces a curtain of water around the front of the torch. The water muffler is always used in conjunction with a water table. The combination of a water curtain at the top of the plate and a water table contacting the bottom of the plate encloses the arc and creates a noise-reducing shield, attenuating noise by roughly 20 decibels (dB). These accessories should not be confused with cutting variations using water injection or water shielding, however.

RESISTANCE WELDING

When selecting resistance welding equipment, personnel safety must be a consideration. All equipment must be installed by qualified personnel under the direction of a technical supervisor in accordance with the *Electrical Standard for Industrial Machinery*, NFPA 79[142] and the *National Electric Code,* NFPA 70[143] or its equivalent. Operators must be properly trained to operate all resistance welding equipment safely.

Machinery Safeguarding

Devices that initiate a resistance welding operation—push buttons, foot switches, retraction, and dual-schedule switches on portable guns, for example—must be

138. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 25.
139. See Reference 87.
140. See Reference 85.
141. See Reference 138.

142. National Fire Protection Association (NFPA), *Electrical Standard for Industrial Machinery,* NFPA 79, Quincy, Massachusetts: National Fire Protection Association.
143. See Reference 110.

arranged or guarded to prevent inadvertent activation.[144] One or more emergency stop buttons must be provided on all welding machines that require three or more seconds to complete a sequence and have mechanical movements that can be hazardous to personnel if the guards are removed. It should be verified that the installation and use of these emergency stop buttons do not in themselves create additional hazards.[145]

Stationary Equipment. All gears, chains, operating linkages, and belts used with welding equipment must be guarded in accordance with ANSI safety standards for mechanical power transmission devices. It is crucial that the operator's hands be kept be away from the point of operation. On stationary single-ram welding machines, an appropriate device must be used to prevent the hands from making contact with the point of operation during the machine cycle unless the size of the workpiece, its configuration, or fixture keeps both of the operator's hands away from the point of operation. Appropriate safety apparatus includes latches, two-handed controls, machine guards, or fixtures to prevent the hands from passing under the point of operation, and presence-sensing equipment. Similar precautions must be taken if the operator's hands need to pass under the point of operation during a multigun welding machine operation.[146]

Portable Equipment. All suspended portable welding gun equipment, except the gun assembly, must be fail safe. It must incorporate a support system that is capable of withstanding the total impact load in case any component of the supporting system should fail. Cables, chains, and clamps are satisfactory support system components.[147]

Moving holder mechanisms on portable welding equipment require additional precautions. A moving holder mechanism that enters the gun frame must be designed to ensure that no sharp shear points could cause injury to fingers. If shear points are present, appropriate guarding must be provided. If adequate guarding from shear cannot be accomplished, the use of two handles—one for each hand—is permitted provided each handle has one or two operating switches at appropriate holding points. These handles and operating switches must be positioned a safe distance away from any shear or pinch point to prevent contact when the hands are on the controls.[148]

Electrical Considerations

All external weld-initiating control circuits must operate at or below 120 V ac for stationary equipment. Portable equipment must operate at or below 36 V ac rms. In addition, resistance welding equipment and control panels containing capacitors used for stored-energy resistance welding involving high voltages (above 550 V ac) must be suitably insulated and protected by complete enclosures. All doors on this equipment must have suitable interlocks and contacts wired into the control circuit. These interlocks or contacts must be designed to interrupt power and short circuit all capacitors when the panel is open. As an added safety measure ensuring absolute discharge of all capacitors, a manual switch or suitable positive device must be installed in addition to the mechanical interlocks or contacts. It is important to note that since the panel box itself is considered an enclosure, the capacitors inside it require no additional protection when all other safety requirements have been met.[149]

To prevent unauthorized access to live portions of equipment, all electrical resistance welding equipment must be locked or interlocked, including all doors and access panels on resistance welding machines and remote control panels that are accessible at floor level. A door or access panel is considered locked when a key, wrench, or other instrument is required to open it. Control panels that are located on overhead platforms or in separate rooms must be locked, interlocked, or guarded by a physical barrier or a sign, except when the equipment is undergoing service. In addition, panel doors must always be closed.[150]

On large welding machines that have a platen, electrically interlocked safety apparatus such as pins, blocks, or latches must be provided when the platen or the head can move. When activated, this safety device must break the energizing circuit. The device itself must prevent movement of the platen or head under static load. Although more than one device may be required, depending on the machine's size or accessibility, each device alone must be capable of sustaining the full static load involved.[151]

To ensure the safety of personnel in the area, protection from flying sparks and molten metal must be provided by a guard of suitable fire-resistant material or approved protective eyewear. For flash welding equip-

144. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 38.
145. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 40.
146. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, p. 39.
147. See Reference 146.
148. See Reference 146.
149. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 39–40.
150. See Reference 145.
151. See Reference 145.

ment, flash guards of suitable fire-restraint material must be provided to control flying sparks and molten metal. In addition, for proper electrical safety, resistance welding equipment must have appropriate grounding. The welding transformer secondary may be grounded by either (1) permanent grounding of the welding secondary circuit or (2) connecting a grounding reactor across the secondary winding with reactor tap(s) to ground. As an alternative on stationary machines, an isolation contactor can be arranged to open both sides of the line to the primary of the welding transformer.[152]

It is important to remember that since resistance welding operations vary each operation must be evaluated individually to provide proper protection.

HIGH-FREQUENCY WELDING

Injuries from high-frequency welding power, especially at the upper range of welding frequencies, tend to produce severe localized surface tissue damage. These injuries are not likely to be fatal, however, because the current flow is shallow and does not penetrate deeply into the body.

On the other hand, high-frequency welding generators, which emit lethal voltages ranging from 400 V to 20,000 V in either low or high frequency, can cause fatal injuries. Thus, proper care and safety precautions must be taken while working on high-frequency welding generators and their control systems. Units must be equipped with safety interlocks on access doors and with automatic safety grounding devices to prevent equipment operation when access doors are open. The equipment must not be operated with the panels or high-voltage covers removed or with the interlocks and grounding devices blocked.[153]

The output high-frequency primary leads must be encased in metal ducting and should not be operated in the open. Induction coils and contact systems must always be properly grounded for operator protection. High-frequency currents are more difficult to ground than low-frequency currents, and grounding lines must be kept short and direct to minimize inductive impedance. The magnetic field from the output system must not induce heat in adjacent metallic sections, which could cause burns or fires.

High-frequency welding stations often emit a loud, steady whine that can cause permanent hearing loss. Ear protection is essential under these circumstances.

152. See Reference 145.
153. This equipment should not be confused with high-frequency arc stabilization equipment, which is used in gas tungsten arc welding.

ELECTRON BEAM WELDING

The standards *Recommended Practices for Electron Beam Welding*, ANSI/AWS C7.1,[154] and *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1,[155] stipulate general safety requirements that must be followed strictly at all times while performing electron beam welding. The primary hazards associated with electron beam welding equipment are electric shock, X-radiation, fumes and gases, and damaging visible radiation. Thus, precautionary measures must be taken at all times. These hazards are discussed below.

Electric Shock

Electron beam welding machines operate at voltages that are much higher than those employed in other welding processes. Electron beam equipment is typically operated at voltages above 20 kV. These voltages can cause fatal injury regardless of whether the machine is labeled as being a low-voltage or a high-voltage device. Even though the manufacturers of electron beam welding equipment produce machines that are well insulated against high voltage, precautions must be taken with all systems when high voltage is present. The manufacturer's instructions should be followed for proper equipment operation and maintenance.

X-Radiation

The X-radiation generated by electron beam welding machines is produced when electrons traveling at high velocity collide with matter. The majority of X-rays are produced when the electron beam impinges upon the workpiece. Substantial amounts are also produced when the beam strikes gas molecules or metal vapor in the gun column and work chamber. Producers and users must follow procedures that adhere to regulations established by Underwriters Laboratories (UL) and OSHA, providing firm rules for permissible X-ray exposure levels.

Electron beam welding and cutting equipment must be properly shielded to block out x-radiation or reduce it to acceptable levels.[156] The steel walls of the chamber are generally adequate protection in systems up to 60 kV, assuming proper design. High-voltage machines utilize lead lining to block X-ray emission beyond the chamber walls. Leaded glass windows are employed in both high- and low-voltage electron beam systems. The

154. American Welding Society (AWS) Committee on High Energy Beam Welding and Cutting, *Recommended Practices for Electron Beam Welding*, AWS C7.1, Miami: American Welding Society.
155. See Reference 1.
156. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1:1999, Miami: American Welding Society, p. 42.

shielded vacuum chamber walls normally provide adequate protection for the operator.

If a system does not have a vacuum, a radiation enclosure must be provided to assure the safety of the operator and others in the work area. Instead of lead, thick walls of high-density concrete or other similar material may be used, especially for large radiation enclosures on nonvacuum installations. Special safety precautions should also be implemented to prevent personnel from accidentally entering or becoming trapped inside the enclosure during equipment operation.

A complete X-ray radiation survey of the electron beam equipment should always be made at the time of installation and at regular intervals thereafter. This survey must be conducted by qualified technicians to ensure initial and continued compliance with all radiation regulations and standards applicable to the site where the equipment is installed. The results should be documented and posted.[157]

Fumes and Gases

Nonvacuum and medium-vacuum electron beam systems can produce ozone and oxides of nitrogen in harmful concentrations as well as other types of airborne contaminants in concentrations above acceptable levels. Therefore, adequate area ventilation must reduce the concentrations of airborne contaminants around the equipment to within permissible exposure limits. Proper exhausting techniques should also be employed to maintain permissible residual concentrations in the area.

High-vacuum electron beam chambers are unlikely to produce ozone and oxides in harmful concentrations because of the small amount of air in the chamber.

Personnel must consult the pertinent MSDSs before welding unfamiliar material or utilizing unfamiliar cleaning products.[158]

Visible Radiation

As the electron beam welding process produces visible, UV, and infrared (IR) radiation, direct viewing of the process can be hazardous to the eyesight. Therefore, adequate optical protection must be provided against UV and IR radiation by the installation of leaded glass in the viewing ports. In addition, visible light must be reduced to a comfortable level by means of the appropriate filters.[159]

157. See Reference 156.
158. American National Standards Institute (ANSI) Accredited Standards Committee Z49, 1999, *Safety in Welding, Cutting, and Allied Processes,* ANSI Z49.1:1999, Miami: American Welding Society, pp. 41–42.
159. See Reference 156.

LASER BEAM WELDING AND CUTTING

The basic hazards associated with laser operation are eye damage, including burns of the cornea or retina, or both; skin burns; electrical shock; respiratory system damage from hazardous materials emitted during operation; and chemical hazards, including contact with cryogenic coolants.

Laser manufacturers are required to qualify their equipment with the U.S. Bureau of Radiological Health (BRH). Electrical components must comply with the standards issued by the National Electrical Manufacturers Association. The use of lasers is governed by OSHA requirements. In all cases, the *American National Standard for Safe Use of Lasers,* ANSI Z136.1, should be adhered to.[160] In addition, a laser safety officer (LSO)—responsible for the protection of personnel and the enforcement of laser safety regulations—must be present at all installations performing laser welding and cutting.[161]

Eye and Skin Hazards

Laser beams can readily inflict eye injury. With laser beams operating at visible or near infrared wavelengths, even a 5 milliwatt (mW) beam can inflict retinal damage. Thus, the use of safety glasses is essential. Glasses appropriate to the specific laser system must be used. Safety glasses substantially transparent to visible light but opaque to specific laser beam outputs are available. Selective filters for ruby, Nd:YAG, and other laser systems are also available. Ordinarily, transparent materials such as glass are opaque to longer infrared wavelengths, such as those produced by carbon dioxide lasers, so clear safety glasses with side shields may be used with these systems. In this case, the only light reaching the eye is from the incandescence of the workpiece. Nevertheless, plasma generation at high powers can cause extreme brilliance, so filter lenses should be used for viewing the operation.

According to the specifications of ANSI Z136.1,[162] laser protective eyewear—whether plain or prescription—must be labeled with the optical density and the wavelengths for which protection is provided. This standard also requires that protection be afforded against secondary radiation. Protection against ultraviolet light, which may leak into the work area, should also be provided by the eyewear.[163]

160. American National Standards Institute (ANSI), *American National Standard for Safe Use of Lasers,* Z136.1, Orlando, Florida: Laser Institute of America (LIA).
161. See Reference 3.
162. American National Standards Institute (ANSI), 1993, *American National Standard for Safe Use of Lasers,* Z136.1-1993, Orlando, Florida: Laser Institute of America (LIA).
163. See Reference 3.

To prevent skin burns, welding personnel must always avoid all contact with laser beams. The burns these produce can be deep and very slow to heal. All laser beams used for welding and cutting are visible only when they impinge on a solid, so workers need to take special precautions to avoid accidental exposure. As a preventive measure, the laser beams can be enclosed, or a safety device can be used to prevent operation of the beam unless its path is unobstructed.

Electrical Hazards

As lasers have high voltages and large capacitor storage devices, the possibility of lethal electric shock is always present during laser beam welding. Hazards range from those inherent in any conventional electrical power source to those common to lasers in general and those unique to the particular laser beam welding and cutting process. As a general precaution, electrical system enclosures should have appropriate interlocks on all access doors and provisions for discharging capacitor banks before entry. All laser equipment should also be appropriately grounded. The manufacturer's recommended safety procedures must be followed at all times.

Respiratory Hazards

Although the fumes and gases produced during laser beam welding and cutting are often not visible, they pose potentially serious respiratory hazards. Hazardous products may be generated from the interaction of the beam and the workpiece, making adequate ventilation and exhaust provisions for laser work areas necessary. For example, the plastic materials used for "burn patterns" to identify beam shape and distribution in high-power carbon dioxide laser systems can generate highly toxic vapors if irradiated in an oxygen-lean atmosphere. In deep-penetration welding, fine metal fume can arise from the joint. In addition, intense plasma generation can produce ozone.

The LSO must ensure that all laser-generated air contaminants are characterized in accordance with applicable regulations. When exposure exceeds acceptable levels as established by Title 29 CFR 1910, Subpart Z and the applicable ACGIH standards, the LSO may require the implementation of control measures such as exhaust ventilation systems, respiratory protection, or process isolation.[164]

164. American National Standards Institute (ANSI), 1993, *American National Standard for Safe Use of Lasers,* Z136.1-1993, Orlando, Florida: Laser Institute of America (LIA), p. 29.

Chemical Hazards

Many hazardous chemicals and gases are used in laser welding and cutting operations. These include toxic or corrosive gases such as chlorine, fluorine, hydrogen chloride, and hydrogen fluoride. Cryogenic gases can cause injuries due to freezing because of their extremely low temperatures. Safety hazards are also associated with the use of laser dye compounds. Manufacturers' material safety data sheets should always be consulted, and appropriate measures must be taken to ensure personnel safety in all cases.

FRICTION WELDING

The risks posed by friction welding include mechanical hazards, heat, and spatter. To minimize the risk of injury, friction welding machines should be equipped with appropriate mechanical guards and shields. They should also have two-hand operating switches and electrical interlocks to prevent machine operation when the operator or others have access to the work area, rotating drive, or force system.

Friction welding machines are similar to machine tool lathes in that one workpiece is rotated by a drive system and to hydraulic presses in that one workpiece is forced against the other. Thus, operating personnel should wear the eye protection and safety apparel that is commonly used for machine tool operations. Also, the applicable Occupational Safety and Health Administration (OSHA) standards should be strictly observed.

EXPLOSION WELDING

Explosives and explosion devices are an integral part of explosion welding. If these devices are misused, they can cause injury, death, property damage, and destruction. Although these materials are inherently hazardous, safe practices can minimize the risks associated with their handling. For this reason, explosive materials must be used only by trained personnel who are experienced in their safe handling.

Handling and safety procedures must comply with all applicable federal, state, and local regulations. The U.S. Bureau of Alcohol, Tobacco, and Firearms; the Hazardous Materials Regulation Board of the U.S. Department of Transportation; OSHA; and the Environmental Protection Agency (EPA) have federal jurisdiction on the sale, transport, storage, and use of explosives. Many state and local governments require a blasting license or permit, and some cities have special requirements for explosives.

Other organizations also provide safety education for the handling of explosives. The Institute of Makers of Explosives distributes educational publications to promote the safe handling, storage, and use of explosives. The National Fire Protection Association (NFPA) also provides recommendations for the safe manufacture, storage, handling, and use of explosives.[165]

ULTRASONIC WELDING

Ultrasonic welding may pose the risk of mechanical hazards, electric shock, heat, and burns. In high-power ultrasonic equipment, high voltages are present in the frequency converter, the welding head, and the coaxial cable connecting these components. Thus, the equipment should not be operated when its panel doors are open or its housing covers are removed. Door interlocks are normally installed to prevent the introduction of power to the equipment when its high-voltage circuitry is exposed. As the cables are fully shielded, they should present no hazard if properly connected and maintained.

Because of the hazards associated with clamping force, operators must not place hands or arms in the vicinity of the welding tip when the equipment is energized. In accordance with OSHA regulations, the equipment must have two palm buttons for manual operation. These must be pressed simultaneously to initiate a weld cycle, and both must be released before the next cycle can begin. For automated systems in which the weld cycle is sequenced with other operations, protective guards should be installed to protect operators. As a further precaution, the welding stroke can be set to the minimum that is compatible with workpiece clearance.

THERMITE WELDING

Thermite welding is a process that utilizes the thermochemical reaction between metal oxide and aluminum to produce the heat to form a weld. Moisture in the thermite mix, whether in storage, in the crucible, or on the workpieces, can rapidly emit steam during the chemical reaction for thermite welding. This may cause the ejection of molten metal from the crucible. To minimize the risk of steam formation, the thermite mix should be stored in a dry place, the crucible should be dry, and moisture should not be permitted to enter the system prior to or during welding.

The preheating required for the thermite process should be carried out using the safety precautions applicable to oxyfuel gas equipment and operations. The work area should be free of materials that may be ignited by sparks or small particles of molten metal. The area should also be well ventilated to prevent the buildup of fumes and gases from the thermite reaction. Starting powders and rods should be protected against accidental ignition.

Personnel should use appropriate personal protective equipment to shield against hot particles or sparks. Full-face shields with filter lenses for eye protection, headgear, gloves, and safety boots should be used. Clothing should not have pockets or cuffs that might catch hot particles.

BRAZING AND SOLDERING

The hazards encountered in brazing and soldering operations are similar to those associated with the welding and cutting processes.[166] Personnel and property must be protected against gases, fumes, hot materials, electrical shock, radiation, and chemicals.[167] As hazardous materials may be present in the fluxes, filler metals, coatings, and atmospheres used in brazing, the material safety data sheets should be consulted as a prerequisite to any job.

Hazardous and Explosive Gases and Fumes

Brazing and soldering operations may be performed at temperatures that induce some elements in the filler metal to vaporize into fumes and gases. Some of these elements are hazardous. These include cadmium, beryllium, zinc, mercury, and lead. Thus, it is essential that adequate ventilation be provided to protect personnel from inhaling the gases and fumes emitted during brazing or soldering. Brazing fluxes may also contain chemical compounds of fluorine, chlorine, and boron. These compounds are harmful if they are inhaled or come into contact with the eyes or skin. Ventilation methods used to avoid these hazards have been described above (see the section titled "Ventilation").

Flammable gases, such as combusted fuel gas, hydrogen, and disassociated ammonia, are sometimes used as atmospheres for furnace brazing operations. Before introducing such atmospheres, the furnace or retort must be purged of air by safe procedures recommended by the furnace manufacturer. These gases may emanate from furnace purging and brazing operations. Thus, adequate area ventilation must exhaust and discharge explosive or hazardous gases to a safe location. Local

165. See National Fire Protection Association (NFPA), *Explosive Materials Code,* NFPA 495, Quincy, Massachusetts: National Fire Protection Association.

166. For additional information on brazing and soldering safety, see Chapter 6 of American Welding Society (AWS) Committee on Brazing and Soldering, 20XX, *Brazing Handbook,* Miami: American Welding Society.

167. Safety procedures for furnaces and oven processes are provided in National Fire Protection Association (NFPA), *Standard for Ovens and Furnaces,* NFPA 86, Quincy, Massachusetts: National Fire Protection Association; and National Fire Protection Association (NFPA), *Industrial Furnaces using Vacuum as an Atmosphere,* NFPA 86D, Quincy, Massachusetts: National Fire Protection Association.

environmental regulations should be consulted when designing the exhaust system.

In dip brazing and soldering, the parts to be immersed in the bath must be completely dry. Any moisture on the parts instantly creates steam. The expanding steam may then cause an explosion, expelling the contents of the dip pot and creating a serious burn hazard. If supplementary flux is necessary, it must be adequately dried to remove all moisture and water of hydration to prevent the hazard of explosion.

Solder Flux

Some fluxes, such as rosin, petrolatum, and reaction types, emit considerable smoke, the amount depending on the soldering temperature and the duration of heating. Other fluxes emit fumes that are hazardous if inhaled in large quantities. The prolonged inhalation of halides and some of the newer organic fluxes must be avoided. Aniline fluxes and some of the other amines also emit harmful fumes that can cause dermatitis. The fluorine in flux is also hazardous to health. It causes skin burns and can be fatal if ingested.

The American Conference of Governmental Industrial Hygienists (ACGIH) has established the safe threshold limit value for the decomposition products of rosin-core solder at 0.1 milligram per cubic meter (mg/m^3) aliphatic aldehydes, measured as formaldehyde. Suitable ventilation must be provided to meet this requirement. When ventilation is insufficient to reduce contaminants or the implementation of ventilation is not feasible, personnel must utilize the appropriate approved respiratory protective equipment.

THERMAL SPRAYING

All thermal spraying processes involve the depositing of molten metallic or nonmetallic materials to coat an object. These processes utilize modifications of oxyfuel, arc, and plasma energy sources to create the high temperatures and projectile velocities required to perform spray operations. These operations present safety hazards to all individuals in the work area. Thus, the safe practices described above for these processes should be implemented when conducting thermal spraying activities with similar equipment. However, thermal spraying generates dust and fumes to a greater degree.[168]

Those involved with and in the proximity of thermal spraying operations must take precautions against dust, fire, electrical shock, arc radiation, fumes and gases, and noise. Thermal spray operators must be protected with the proper eye, respiratory, and bodily protection. Appropriate protective clothing required for a thermal spraying operation will vary with the size, nature, and location of the work performed.

Dust

Finely divided airborne solids, especially metal dusts, must be treated as an explosive and inhalation hazard. Therefore, the dust produced during thermal spraying must be adequately vented out of spray booths. Instead of bag and filter collectors, a water-wash wet collector is recommended to collect spray dust. Good housekeeping in the work area prevents the accumulation of metal dusts, particularly on rafters, the tops of booths, and in floor cracks. Paper, wood, oily rags, and other combustibles that could cause a fire in the spraying area should be removed before the equipment is operated. Clothing should be fastened tightly around the wrists and ankles to keep dusts from contacting the skin. When personnel work in confined areas, they should wear flame-resistant clothing and gloves.

Electrical Shock

The high voltages used in the thermal spraying processes increase the hazard of electrical shock. Thus, general safety precautions for the avoidance of electric shock must be implemented to protect personnel.

Radiation

As thermal spraying processes generate both UV and IR radiation, helmets, hand shields, face shields, or eye protection must be used to protect the eyes, face, and neck at all times. Safety goggles must be worn to avoid eye damage and burns. Table 17.3 presents a guide for

Table 17.3
Recommended Eye Filter Plates for Thermal Spraying Operations

Operation	Filter Shade Numbers
Wire flame spraying (except molybdenum)	5
Wire flame spraying of molybdenum	5 to 6
Flame spraying of metal powder	5 to 6
Flame spraying of exothermics or ceramics	5 to 8
Plasma and arc spraying	9 to 12
Fusing operations	5 to 6

*When cadmium is a constituent in a filler metal, a precautionary label must be affixed to the container or coil. Refer to Section 9 of ANSI Z49.1:1999 (ANSI 1999a, 20–22).

Source: Adapted from O'Brien, R. L., 1991, Welding Processes, Vol. 2 of *Welding Handbook*, 8th ed., Miami: American Welding Society, Table 28.7

168. Additional information may be found in American Welding Society (AWS) Committee on Thermal Spraying, 1985, *Thermal Spraying: Practice, Theory, and Application*, Miami: American Welding Society.

the selection of the proper filter shade number for viewing specific spraying operations.

The intense UV radiation of plasma and electric arc spraying can cause skin burns through normal clothing. Thus, the protection against radiation that is used during arc spraying is practically the same as that employed for arc welding at equivalent current levels.

Fumes and Gases

Most thermal spraying operations require operators to wear adequate respiratory protection. The nature, type, and magnitude of the fume and gas exposure determine which respiratory protective device should be used. All devices used must be approved by the Mine Safety and Health Administration (MSHA), the National Institute for Occupational Safety and Health (NIOSH), or other recognized authority.

Noise

Thermal spraying operations generate noise in high decibel ranges. Consequently, noise control programs must be implemented in accordance with Title 29 CFR 1910.95. In addition, operators and others in the area should wear earmuffs or properly fitted soft rubber earplugs.

ADHESIVE BONDING

As corrosive materials, flammable liquids, and hazardous substances are commonly used in adhesive bonding, adequate safety precautions must be observed in compliance with all federal, state, and local regulations, including *Air Contaminants,* Title 29 CRF 1900.1000.

Safety Facilities

Management must properly supervise manufacturing operations to ensure that proper safety procedures, protective devices, and protective clothing are employed. Areas in which adhesives are handled should be separated from those in which other operations are performed. In addition to being equipped with the proper fire protection equipment, these areas should have ventilating facilities, a first aid kit, a sink with running water, and an eye shower or rinse fountain. To ensure proper ventilation, ovens, presses, and other curing equipment should be individually vented to remove fumes. Vent hoods should be provided at mixing and application stations.

All personnel should also practice good personal hygiene. They should be instructed in the proper procedures to prevent skin contact with solvents, curing agents, and uncured base adhesives. Showers, wash bowls, mild soaps, clean towels, refatting creams, and protective equipment should be available. Curing agents on hands should be cleaned off with soap and water. Resins should be removed with soap and water, alcohol, or a suitable solvent. Solvents should be used sparingly; following use, they should washed off with abundant soap and water. If an allergic reaction or burning occurs, prompt medical attention should be sought.

Personal Protective Equipment

While working with potentially hazardous adhesives, personnel must wear plastic or rubber gloves at all times. Contaminated gloves should never touch objects that others may touch with their bare hands. Instead, these gloves should be discarded or cleaned using procedures that remove the particular adhesive. Cleaning may require solvents, soap and water, or both. The hands, arms, face, and neck should be coated with a commercial barrier ointment or cream, which provides short-term protection and makes adhesives easier to wash off the skin.

Full-face shields should be worn for eye protection whenever the possibility of splashing exists. Otherwise, glasses or goggles should be worn. In case of irritation, the eyes should be flushed immediately with water and then promptly treated by a physician.

Protective clothing should be worn at all times by those who work with adhesives. Shop coats, aprons, or coveralls may be suitable, and they should be cleaned before reuse.

Flammable and Hazardous Materials

To prevent fires during the storage and use of flammable materials such as solvents, these hazardous materials must be stored in tightly sealed drums and issued in suitably labeled safety cans. Solvents and flammable liquids must not be used in poorly ventilated confined areas. When solvents are used in trays, safety lids should be provided. Flames, sparks, or spark-producing equipment must not be permitted in the area where flammable materials are being handled. In addition, fire extinguishers should be readily available.

Factors to be considered in identifying the types of precautionary measures that should be implemented while working with hazardous materials include the frequency and duration of exposure, the degree of hazard associated with a specific adhesive, the solvent or curing agent used, the temperature at which the operations are performed, and the potential evaporation surface area exposed at the workstation.

For most personnel, preventing skin contact with an adhesive should be an adequate safety measure. It is mandatory that protective equipment, barrier creams, or both be used to avoid skin contact with certain types of formulations. However, others may suffer severe allergic reactions produced by direct contact with or the inhalation or ingestion of phenolics, epoxies, and most catalysts and accelerators. The eyes or skin may become sensitized over a long period of time although no signs of irritation are visible. Once personnel become sensitized to a particular adhesive, they may no longer be able to work in its vicinity because of allergic reactions.

Proper safety rules must be observed to prevent the careless handling of adhesives and thereby prevent exposure to hazardous materials. For example, personnel performing adhesive bonding with potentially hazardous materials should avoid contact tools, doorknobs, light switches, or other objects that may become contaminated.

SAFETY IN ROBOTIC OPERATIONS

The hazards associated with robotic welding, cutting, and allied process are those generally related to (1) equipment (e.g., faulty power sources, protective devices, control circuits, and so on), (2) installations (human errors during setup, ergonomics, maintenance, mounting, positioning, loose objects, and so forth), and (3) the robot system itself or its interaction with other equipment and persons (e.g., moving components that cause trapping or crushing, hazardous atmospheres, inadvertent operation, and so forth).[169]

Personnel must be safeguarded against hazards during all stages of robotic system implementation—design and development, installation and integration, verification, operation, and maintenance. Safeguarding is the responsibility of those involved in all of these stages. In addition, the user must ensure that all personnel are trained in robotic system operation and that the appropriate safeguarding devices are installed and functioning. Awareness signals (signs, lights, floor markers, horns, and beepers, for example) and barriers should be used in conjunction with safeguarding devices.[170]

The welding process equipment may have specific additional safety requirements regarding barriers, guarding, and precautionary labels. The safety requirements of the welding process that is performed by the robotic system must be implemented. In addition, the testing and startup of robots and robotic systems must be performed according to the specifications of *American National Standard for Industrial Robots and Robot Systems—Safety Requirements,* ANSI/RIA R15.06-1999.[171]

Inasmuch as robotic installations vary significantly from application to application, they must be scrutinized individually for specific safety hazards. During the design stage and again upon completing the final configuration and setup of an installation, the user or integrator must perform a risk assessment of the installation. This assessment involves a task and hazard identification as well as a risk estimation. The selection of the appropriate safeguards is based on the information collected and documented as part of the risk assessment.[172]

Among the safeguarding devices that may be used to protect personnel are barriers; two-hand controls; and presence-sensing devices (PSSD), including area scanning systems, single and multiple safety beams, safety mats, and safety light curtains or screens.[173] Figure 17.8 shows several typical robotic installations.

With respect to personnel training, the user must ensure that individuals who program, teach, operate, or maintain robots are properly trained in the tasks performed by the robot, the hazards presented by the system, health and safety procedures, and the purpose and function of safeguarding devices. Training must include general and emergency workplace safety procedures, industry codes and standards, vendor safety information, and lockout and tagout procedures. Maintenance personnel must be trained in emergency operations as well as in the hazards related to process variables and materials, preventive maintenance, troubleshooting, faulty safety devices and communication systems. Retraining is required to ensure safe operation following personnel or system changes or an accident.[174]

For detailed information regarding the safety regulations governing robotic operations, the reader is encouraged to consult the *American National Standard for Industrial Robots and Robot Systems—Safety*

169. American National Standards Institute (ANSI), 1999, *American National Standard for Safety Requirements for Industrial Robots and Robot Systems*, ANSI/RIA R15.06-1999, Ann Arbor: Robotic Industries Association, p. 21.
170. American National Standards Institute (ANSI), 1999, *American National Standard for Safety Requirements for Industrial Robots and Robot Systems*, ANSI/RIA R15.06-1999, Ann Arbor: Robotic Industries Association, pp. 20–22.
171. American National Standards Institute (ANSI), 1999, *American National Standard for Safety Requirements for Industrial Robots and Robot Systems*, ANSI/RIA R15.06-1999, Ann Arbor: Robotic Industries Association, pp. 42–43.
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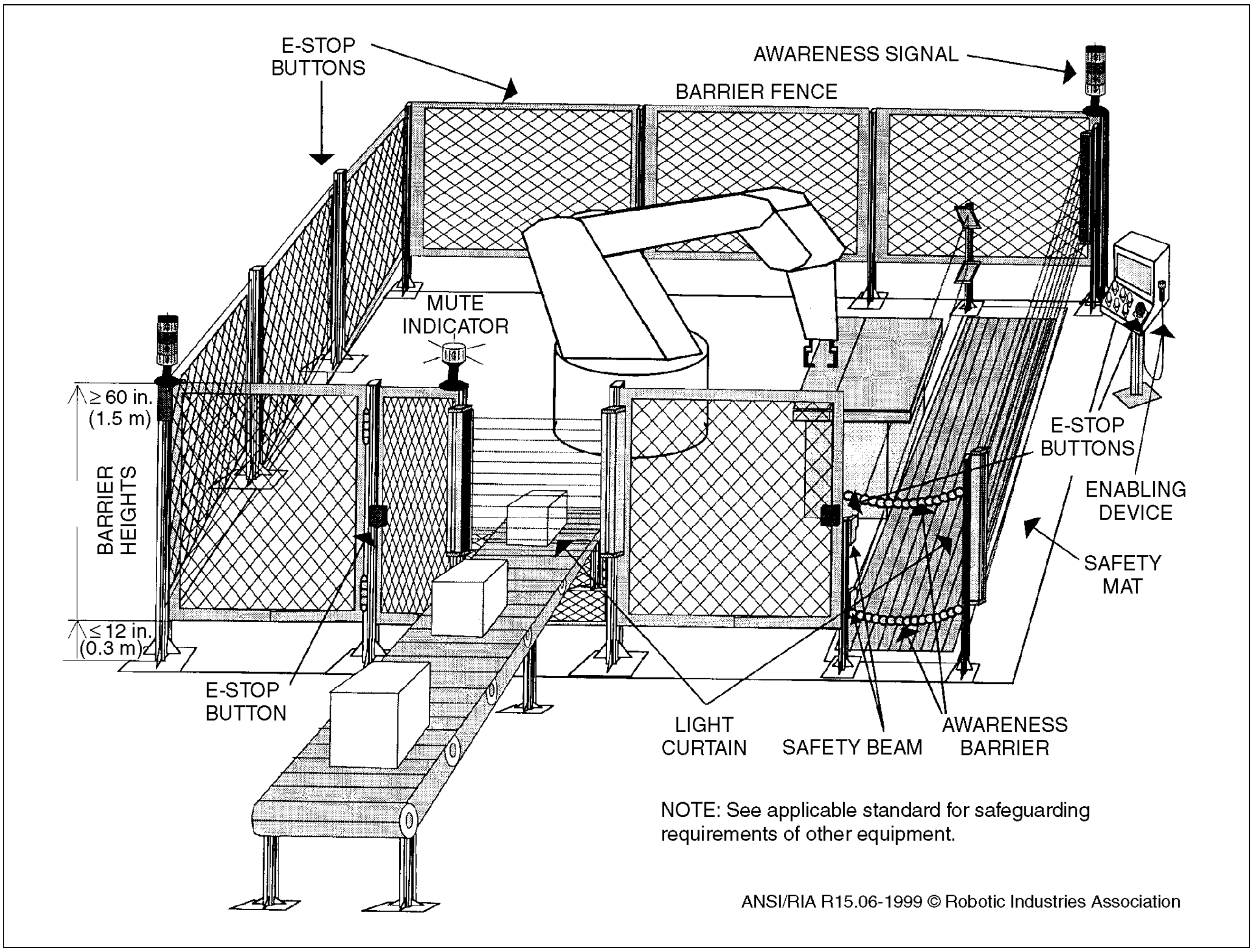

Source: Adapted, with permission, from American National Standards Institute (ANSI), 1999, *American National Standard for Safety Requirements for Industrial Robots and Robot Systems*, ANSI/RIA 15.06-1999, Ann Arbor: Robotic Industries Association, Figure A.3.

Figure 17.8—Typical Robotic Cell with Safeguarding Devices

Requirements, ANSI/RIA R15.06-1999, the primary industry standard.[175]

CONCLUSION

The protection of personnel and property from the hazards posed by welding, cutting, and allied processes is a primary industry concern. The information presented in this chapter is by no means comprehensive, and the body of knowledge on the topic of safe practices is constantly being revised, refined, and expanded. The reader is therefore strongly encouraged to consult the latest regulations, codes, standards, manufacturers' instructions, and manufacturers' material safety data sheets for additional information and guidance.

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DEDICATION

William L. Green
1925–1998

Robert L. O'Brien
1927–1998

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

W. L. Green served as Chair of the Welding Handbook Committee on Symbols for Joining and Inspection for this volume of the *Welding Handbook*. He was active in the American Welding Society (AWS) A2 Committees, which promote the accurate communication of welding technology through the development of standard terms, definitions, and welding engineering symbols.

The American Welding Society recognized W. L. Green in 1963 with the Adams Memorial Membership Award for his outstanding work as an engineering educator at The Ohio State University. Over a period of 30 years, he developed and taught courses in the areas of welding design, codes, procedure development, process applications, manufacturing systems, and the testing and inspection of welds.

R. L. O'Brien was editor of *Welding Processes*, Volume 2 of the eighth edition of the *Welding Handbook*, which was published in 1991. He was active in the AWS C5 Committees on plasma arc welding and cutting. His career included research and original development work with plasma arc welding and cutting for the former Linde Company, a division of Union Carbide, where he held various technical, training, and managerial positions. As a member of the American Welding Society staff, he served in several technical and educational capacities. He was editor of the eighteenth edition of *Jefferson's Welding Encyclopedia*, published in 1997.

R. L. O'Brien received the American Welding Society's Plummer Memorial Educational Lecture award in 1963. In 1998, he was posthumously granted the AWS Honorary Membership award for exceptional accomplishments in the industry.

W. L. (Bill) Green and R. L. (Bob) O'Brien were Life Members of the American Welding Society. Both made substantial contributions to welding technology and enjoyed being a part of the profession. Both shared their technical knowledge freely and enthusiastically, Bill Green as an educator and Bob O'Brien as an author, editor, and lecturer. Both were highly regarded, honorable human beings whose integrity enriched the welding industry.

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APPENDIX A

TERMS AND DEFINITIONS

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APPENDIX A

TERMS AND DEFINITIONS

INTRODUCTION

During the mid-1930s, the American Welding Society (AWS) recognized the necessity of establishing a standard vocabulary to communicate the increasingly complex technology of welding and responded to this need by forming the AWS Committee on Definitions and Symbols. The current edition of *Standard Welding Terms and Definitions*, AWS A3.0:2001,[1,2] an American National Standard, is the cumulative product of the work of the AWS Subcommittee on Definitions in support of that purpose. The publication defines 1357 terms, presents 58 illustrations to clarify the definitions, and provides classification charts and corollary information for the welding processes.

This appendix is adapted from *Standard Welding Terms and Definitions*, AWS A3.0:2001.[3] It presents a glossary of standard welding terms and definitions and includes terms for adhesive bonding, brazing, soldering, thermal spraying, and thermal cutting. Commentary and illustrations are also selected from this document. The reader is referred to the latest edition of *Standard Welding Terms and Definitions*, AWS A3.0,[4] for the most current and complete welding vocabulary and related information.

The standard terms and definitions in the glossary should be used in the oral and written language of welding. It is recommended that standard terms be used in all welding literature. The use of these terms is particularly important in the writing of standards (codes, specifications, recommended practices, methods, classifications, and guides) and legal documents such as contracts, laws, and regulations.

Because the glossary is intended to be a comprehensive compilation of welding terminology, nonstandard terms used in the welding industry are included, although not recommended. The terms printed in bold type in the glossary are standard terms; nonstandard terms are identified as such. Terms for standard welding processes and process variations are followed by their standard letter designations. The terms are arranged in the conventional dictionary-style alphabetical sequence. Only generic terms and definitions are included; proprietary brand and trademark names commonly used to describe welding processes, equipment, and filler metals are excluded.

The illustrations in this appendix are not sequenced in their order of reference in the alphabetical listing but are grouped by general categories because several of them illustrate more than one term or definition. Figures A.1 through Figure A.7 illustrate joint types and configurations. Figures A.8 through A.11 illustrate welding positions. Figures A.12 and A.13 illustrate weld sequence and weld nomenclature. The schematic drawings in Figure A.14 illustrate groove weld sizes and joint penetration. Figure A.15 identifies weld discontinuities, and Figure A.16 illustrates crack types.

The Master Chart of Welding and Joining Processes, presented in Figure A.17, and the Master Chart of Allied Processes, presented in Figure A.18, are visual displays of a hierarchy of processes, with the highest generic level (least specific) in the center and the more specific level in boxes around the perimeter. Some of the

1. American Welding Society (AWS) Committee on Definitions, 2001, *Standard Welding Terms and Definitions,* AWS A3.0:2001, Miami: American Welding Society.
2. At the time of the preparation of this appendix, the referenced codes and 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 document referred to applies. If a code or 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. See Reference 1.
4. American Welding Society (AWS) Committee on Definitions. *Standard Welding Terms and Definitions*. Miami: American Welding Society.

process variations are also included in the boxes. For historical reasons, the basis for classification is not entirely consistent; the determining factors include the energy source, capillary flow, and the physical state of the base material at the time of welding (i.e., liquid versus solid).

The Joining Method Chart in Figure A.19 is based exclusively on the physical state of materials at the joint during coalescence. It summarizes the three classification charts that follow: Figure A.20, Fusion Welding Classification Chart; Figure A.21, Solid-State Welding Classification Chart; and Figure A.22, Brazing and Soldering Classification Chart. These charts illustrate the three major classifications of the welding and joining processes: (1) fusion welding for a liquid/liquid interface, (2) solid-state welding for a solid/solid interface, and (3) brazing and soldering for a liquid/solid interface.

For convenience, the 126 welding, cutting, allied processes and their variations have been assigned a letter designation. These letter designations are listed in Table A.1. These designations are useful in speaking or writing about the welding processes and are especially useful in communicating them in drawings and specifications. An alphabetical cross-reference to Table A.1 by process is presented in Table A.2.

GLOSSARY

A

abrasion soldering. A soldering process variation during which the faying surface of the base metal is mechanically abraded.

abrasive blasting. A method of cleaning or surface roughening by a forcibly projected stream of abrasive particles.

absorptive lens. A filter lens designed to attenuate the effects of glare and reflected and stray light. See also **filter plate**.

accelerating potential, *electron beam welding* and *electron beam cutting*. The potential that imparts velocity to the electrons.

acceptable weld. A weld that meets the applicable requirements.

acetylene feather. The intense white, feathery-edged portion adjacent to the cone of a carburizing oxyacetylene flame.

acid core solder. A solder wire or bar containing acid flux as a core.

activated rosin flux. A rosin base flux containing an additive that increases wetting by the solder.

active flux, *submerged arc welding*. A flux formulated to produce a weld metal composition that is dependent on the welding parameters, especially arc voltage. See also **alloy flux** and **neutral flux**.

actual throat. The shortest distance between the weld root and the face of a fillet weld. See also **effective throat** and **theoretical throat**.

adaptive control, *adj*. Pertaining to process control that automatically determines changes in process conditions and directs the equipment to take appropriate action. See also **automatic**, **manual**, **mechanized**, **robotic**, and **semiautomatic**.

adaptive control brazing. See **adaptive control welding**.

adaptive control soldering. See **adaptive control welding.**

adaptive control thermal cutting. See **adaptive control welding.**

adaptive control thermal spraying. See **adaptive control welding.**

adaptive control welding. Welding with a process control system that automatically determines changes in welding conditions and directs the equipment to take appropriate action. Variations of this term are **adaptive control brazing, adaptive control soldering, adaptive control thermal cutting**, and **adaptive control thermal spraying**. See also **automatic welding, manual welding, mechanized welding, robotic welding**, and **semiautomatic welding**.

adhesive. A polymeric material having chemical and physical properties differing from those of the base materials placed at the faying surfaces to join the materials together as a result of the attractive forces of this polymeric material.

adhesive bond. An attraction, generally physical in nature, between an adhesive and the base materials.

adhesive bonding (AB). A joining process in which an adhesive, placed between faying surfaces, solidifies to produce an adhesive bond.

agglomerated flux, *submerged arc welding.* A granular flux produced by baking a pelletized mixture of powdered ingredients and bonding agents at a temperature sufficient to remove the water, followed by processing to produce the desired particle size. See also **bonded flux** and **fused flux**.

air acetylene welding (AAW). An oxyfuel gas welding process that uses an air-acetylene flame. The process is used without the application of pressure. This is an obsolete or seldom used process.

air cap. A nonstandard term for the nozzle of a flame spraying gun for wire or ceramic rod.

air carbon arc cutting (CAC-A). A carbon arc cutting process variation that removes molten metal with a jet of air.

air carbon arc cutting torch. A device used to transfer current to a fixed cutting electrode, position the electrode, and direct the flow of air.

air feed. A thermal spraying process variation in which an air stream carries the powdered surfacing material through the gun and into the heat source.

aligned discontinuities. Three or more discontinuities aligned approximately parallel to the weld axis, spaced sufficiently close together to be considered a single intermittent discontinuity.

aligned porosity. A localized array of porosity oriented in a line.

alloy. A substance with metallic properties and composed of two or more chemical elements of which at least one is a metal.

alloy flux, *submerged arc welding.* A flux containing ingredients that react with the filler metal to establish a desired alloy content in the weld metal. See also **active flux** and **neutral flux**.

alloy powder. Powder prepared from a homogeneous molten alloy or from the solidification product of such an alloy. See also **powder blend**.

angle of bevel. See **bevel angle**.

arc. See **welding arc**.

arc blow. The deflection of an arc from its normal path due to magnetic forces.

arc braze welding (ABW). A braze welding process variation that uses an electric arc as the heat source. See also **carbon arc braze welding**.

arc chamber. A nonstandard term for **plenum chamber**.

arc cutter. See **thermal cutter**.

arc cutting (AC). A group of thermal cutting processes that severs or removes metal by melting with the heat of an arc between an electrode and the workpiece.

arc cutting gun. A device used to transfer current to a continuously fed cutting electrode, guide the electrode, and direct the shielding gas.

arc cutting operator. See **thermal cutting operator**.

arc cutting torch. See **air carbon arc cutting torch, gas tungsten arc cutting torch,** and **plasma arc cutting torch**.

arc force. The axial force developed by an arc plasma.

arc gap. A nonstandard term when used for **arc length**.

arc gas. A nonstandard term when used for **orifice gas**.

arc gouging. Thermal gouging that uses an arc cutting process variation to form a bevel or groove.

arc length. The distance from the tip of the welding electrode to the adjacent surface of the weld pool.

arc oxygen cutting. A nonstandard term for **oxygen arc cutting**.

arc plasma. A gas that has been heated by an arc to at least a partially ionized condition, enabling it to conduct an electric current.

arc seam weld. A seam weld made by an arc welding process. See Figures A.7(A) and A.7(B).

arc seam weld size. See **seam weld size.**

arc spot weld. A spot weld made by an arc welding process.

arc spot weld size. See **spot weld size.**

arc sprayer. See **thermal sprayer.**

arc spraying (ASP). A thermal spraying process using an arc between two consumable electrodes of surfacing materials as a heat source and a compressed gas to atomize and propel the surfacing material to the substrate.

arc spraying operator. See **thermal spraying operator.**

arc strike. A discontinuity resulting from an arc, consisting of any localized remelted metal, heat-affected metal, or change in the surface profile of any metal object.

arc stud welding (SW). An arc welding process that uses an arc between a metal stud, or similar part, and the other workpiece. The process is used without filler metal, with or without shielding gas or flux, with or without partial shielding from a ceramic or graphite ferrule surrounding the stud, and with the application of pressure after the faying surfaces are sufficiently heated.

arc time. The time during which an arc is maintained in making an arc weld.

arc voltage, *arc welding*. The electrical potential between the electrode and workpiece.

arc welding (AW). A group of welding processes that produces coalescence of workpieces by heating them with an arc. The processes are used with or without the application of pressure and with or without filler metal.

arc welding deposition efficiency. The ratio of the weight of filler metal deposited in the weld metal to the weight of filler metal melted, expressed in percent.

arc welding electrode. A component of the welding circuit through which current is conducted and that terminates at the arc.

arc welding gun. A device used to transfer current to a continuously fed consumable electrode, guide the electrode, and direct the shielding gas.

arc welding torch. A device used to transfer current to a fixed welding electrode, position the electrode, and direct the shielding gas.

arm, *resistance welding*. A projecting beam extending from the frame of a resistance welding machine that transmits the electrode force and may conduct the welding current.

as-brazed, *adj*. Pertaining to the condition of brazements after brazing, prior to any subsequent thermal, mechanical, or chemical treatments.

assist gas. A gas used to blow molten metal away to form the kerf in laser beam inert gas cutting, or to blow vaporized metal away from the beam path in laser beam evaporative cutting.

as-welded, *adj*. Pertaining to the condition of weld metal, welded joints, and weldments after welding, but prior to any subsequent thermal, mechanical, or chemical treatments.

atomic hydrogen welding (AHW). An arc welding process that uses an arc between two metal electrodes in a shielding atmosphere of hydrogen and without the application of pressure. This is an obsolete or seldom used process.

autogenous weld. A fusion weld made without filler metal.

automatic, *adj*. Pertaining to the control of a process with equipment that requires only occasional or no observation of the welding, and no manual adjustment of the equipment controls. See also **adaptive control, manual, robotic,** and **semiautomatic.**

automatic arc welding current. The current in the welding circuit during the making of a weld, but excluding upslope, downslope, and crater fill current.

automatic arc welding downslope time. The time during which the current is changed continuously from final taper current or welding current to final current.

automatic arc welding upslope time. The time during which the current changes continuously from the initial current to the welding current.

automatic arc welding weld time. The time interval from the end of start time or end of upslope to beginning of crater fill time or beginning of downslope.

automatic brazing. See **automatic welding.**

automatic gas cutting. A nonstandard term for **automatic oxygen cutting.**

automatic soldering. See **automatic welding.**

automatic thermal cutting. See **automatic welding.**

automatic thermal spraying. See **automatic welding.**

automatic welding. Welding with equipment that requires only occasional or no observation of the welding and no manual adjustment of the equipment controls. Variations of this term are **automatic brazing, automatic soldering, automatic thermal cutting,** and **automatic thermal spraying**. See **adaptive control welding, manual welding, mechanized welding, robotic welding,** and **semiautomatic welding.**

auxiliary enlarger. A nonstandard term for **auxiliary magnifier.**

auxiliary magnifier. An additional lens used to magnify the field of vision.

axis of weld. See **weld axis.**

B

back bead. A weld bead resulting from a back weld pass.

back cap. A device used to exert pressure on the collet in a gas tungsten arc welding torch and create a seal to prevent air from entering the back of the torch.

backfire. The momentary recession of the flame into the welding tip, cutting tip, or flame spraying gun, followed by immediate reappearance or complete extinction of the flame, accompanied by a loud report.

backgouging. The removal of weld metal and base metal from the weld root side of a welded joint to facilitate complete fusion and complete joint penetration upon subsequent welding from that side.

backhand welding. A welding technique in which the welding torch or gun is directed opposite to the progress of welding. See also **drag angle, forehand welding, push angle, travel angle,** and **work angle.**

backing. A material or device placed against the back side of the joint adjacent to the joint root, or at both sides of a joint in electroslag and electrogas welding, to support and shield molten weld metal. The material may be partially fused or remain unfused during welding and may be either metal or nonmetal. See Figure A.5(D).

backing bead. A weld bead resulting from a backing weld pass.

backing filler metal. A nonstandard term for **consumable insert.**

backing gas. Backing in the form of a shielding gas employed primarily to provide a protective atmosphere.

backing ring. Backing in the form of a ring, generally used in the welding of pipe.

backing shoe. A backing device used in electroslag and electrogas welding that remains unfused during welding.

backing weld. Backing in the form of a weld. See Figure A.13(D).

backing weld pass. A weld pass resulting in a backing weld.

backstep sequence. A longitudinal sequence in which weld passes are made in the direction opposite to the progress of welding. See Figure A.12(A).

backup, *flash* and *upset welding***.** A locator used to transmit all or a portion of the upset force to the workpieces or to aid in preventing the workpieces from slipping during upsetting.

back weld. A weld made at the back of a single groove weld. See Figure A.13(C).

back weld pass. A weld pass resulting in a back weld.

balling up. The formation of globules of molten filler metal or flux due to lack of wetting of the base metal.

bare electrode. A filler metal electrode that has been produced as a wire, strip, or bar with no coating or covering other than that incidental to its manufacture or preservation.

bare metal arc welding (BMAW). An arc welding process that uses an arc between a bare or lightly coated electrode and the weld pool. The process is used without shielding, without the application of pressure, and filler metal is obtained from the electrode. This is an obsolete or seldom used process.

base material. The material that is welded, brazed, soldered, or cut. See also **base metal** and **substrate.**

base metal. The metal or alloy that is welded, brazed, soldered, or cut. See also **base material** and **substrate.**

base metal test specimen. A test specimen composed wholly of base metal.

base metal zone (BMZ). The portion of the base metal adjacent to a weld, braze or solder joint or thermal cut that has not been affected by the welding, brazing, soldering, or thermal cutting. See Figure A.13(G).

base plate. A nonstandard term when used for **base metal**.

bead. See **weld bead.**

bead weld. A nonstandard term for **surfacing weld.**

beam divergence. The expansion of a beam's cross section as the beam emanates from its source.

bend test. A test in which a specimen is bent to a specified bend radius. See also **face bend test, root bend test**, and **side bend test.**

berry formation. A nonstandard term for **nozzle accumulation.**

bevel. An angular edge shape. See Figure A.4.

bevel angle. The angle between the bevel of a joint member and a plane perpendicular to the surface of the member. See Figure A.4.

bevel edge shape. A type of edge shape in which the prepared surface or surfaces lies at some angle other than perpendicular to the material surface.

bevel face. The prepared surface of a bevel edge shape. See Figures A.4(G) and A.4(H). See also **groove face** and **root face.**

bevel-groove weld. A type of groove weld. See Figures A.5(B) and A.9(B).

bevel radius. The radius used to form a J edge shape. See Figures A.4(B) and A.4(E).

bit. That part of the soldering iron, usually made of copper, that directly transfers heat (and sometimes solder) to the joint.

blacksmith welding. A nonstandard term when used for **forge welding.**

blasting. See **abrasive blasting.**

blind joint. A joint, no portion of which is visible.

block brazing (BB). A brazing process that uses heat from heated blocks applied to the joint. This is an obsolete or seldom used process.

block sequence. A combined longitudinal and cross-sectional sequence for a continuous multiple-pass weld in which separated increments are completely or partially welded before intervening increments are welded. See Figure A.12(B). See also **cascade sequence, cross-sectional sequence, progressive block sequence,** and **selective block sequence.**

blowhole. A nonstandard term when used for **porosity.**

blowpipe. See **brazing blowpipe** and **soldering blowpipe.**

bond. See **covalent bond, ionic bond, mechanical bond,** and **metallic bond.**

bond bar. A nonstandard term for **bond specimen.**

bond cap. A nonstandard term for **bond specimen.**

bond coat, *thermal spraying*. A preliminary (or prime) coat of material that improves adherence of the subsequent thermal spray deposit.

bonded flux, *submerged arc welding*. A granular flux produced by baking a pelletized mixture of powdered ingredients and bonding agents at a temperature below its melting point, but high enough to create a chemical bond, followed by processing to produce the desired particle size. See also **agglomerated flux** and **fused flux.**

bonding. A nonstandard term when used for **brazing, soldering,** and **welding.**

bonding force. The force that holds two atoms together; it results from a decrease in energy as two atoms are brought closer to one another.

bond line, *thermal spraying*. The cross section of the interface between a thermal spray deposit and the substrate.

bond specimen, *thermal spraying*. The test specimen on which a thermal spray deposit has been applied to determine bond strength and thermal spray deposit strength.

bond strength, *thermal spraying*. The unit force required to separate a thermal spray deposit from the substrate.

bottle. A nonstandard term when used for **gas cylinder.**

boxing. The continuation of a fillet weld around a corner of a member as an extension of the principal weld. See Figure A.12(F).

braze. Joining as a result of heating an assembly to the brazing temperature using a filler metal having a liquidus above 450°C (840°F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action.

braze, *v.* The act of brazing.

brazeability. The capacity of a material to be brazed under the imposed fabrication conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service.

braze interface. The interface between braze metal and base metal in a brazed joint.

brazement. An assembly whose component parts are joined by brazing.

braze metal. That portion of a braze that has been melted during brazing.

brazer. One who performs manual or semiautomatic brazing.

braze welding (BW). A joining process that uses a filler metal with a liquidus above 450°C (840°F) and below the solidus of the base metal. The base metal is not melted. Unlike brazing, in braze welding the filler metal is not distributed in the joint by capillary action. See also **arc braze welding, carbon arc braze welding, electron beam braze welding, exothermic braze welding, flow welding,** and **laser beam braze welding.**

brazing (B). A group of joining processes that produces coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 450°C (840°F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action. See Figures A.17, A.19, and A.22.

brazing blowpipe. A device used to obtain a small, accurately directed flame for fine work. A portion of any flame is blown to the desired location by the blowpipe, which is usually mouth operated.

brazing filler metal. The metal or alloy used as a filler metal in brazing, which has a liquidus above 450°C (840°F) and below the solidus of the base metal.

brazing operator. One who operates automatic or mechanized brazing equipment.

brazing procedure. The detailed methods and practices involved in the production of a brazement. See also **brazing procedure specification.**

brazing procedure qualification record (BPQR). A record of brazing variables used to produce an acceptable test brazement and the results of tests conducted on the brazement to qualify a brazing procedure specification.

brazing procedure specification (BPS). A document specifying the required brazing variables for a specific application.

brazing sheet. Brazing filler metal in sheet form.

brazing technique. The details of a brazing operation that, within the limitations of the prescribed brazing procedure, are controlled by the brazer or the brazing operator.

brazing temperature. The temperature to which the base metal is heated to enable the filler metal to wet the base metal and form a brazed joint.

brittle nugget. A nonstandard term when used to describe a faying plane failure in a resistance weld peel test.

bronze welding. A nonstandard term when used for **braze welding.**

buildup. A surfacing variation in which surfacing material is deposited to achieve the required dimensions. See also **buttering, cladding,** and **hardfacing.**

buildup sequence. A nonstandard term for **cross-sectional sequence.**

burnback time. A nonstandard term for **meltback time.**

burner. A nonstandard term when used for **oxyfuel gas cutter.**

burning. A nonstandard term when used for **oxyfuel gas cutting.**

burning in. A nonstandard term for **flow welding.**

burnoff rate. A nonstandard term when used for **melting rate.**

burn-through. A nonstandard term when used for excessive **melt-through** or a hole through a root bead.

burn-through weld. A nonstandard term for an **arc seam weld** or **arc spot weld**.

buttering. A surfacing variation that deposits surfacing metal on one or more surfaces to provide metallurgically compatible weld metal for the subsequent completion of the weld. See also **buildup**, **cladding**, and **hardfacing**.

butting member. A joint member that is prevented, by the other member, from movement in one direction perpendicular to its thickness dimension. For example, both members of a butt joint, or one member of a T-joint or corner joint. See also **nonbutting member**.

butt joint. A joint between two members aligned approximately in the same plane. See Figures A.1(A) and A.2(A).

button. That part of a weld, including all or part of the nugget, that tears out in the destructive testing of spot, seam, or projection welded specimens.

butt weld. A nonstandard term for a weld in a butt joint.

C

cap. A nonstandard term for the final layer of a groove weld.

capillary action. The force by which liquid, in contact with a solid, is distributed between closely fitted faying surfaces of the joint to be brazed or soldered.

carbon arc braze welding (CABW). A braze welding process variation that uses an arc between a carbon electrode and the base metal as the heat source.

carbon arc brazing. A nonstandard term for **twin carbon arc brazing.**

carbon arc cutting (CAC). An arc cutting process that uses a carbon electrode. See also **air carbon arc cutting.**

carbon arc welding (CAW). An arc welding process that uses an arc between a carbon electrode and the weld pool. The process is used with or without shielding and without the application of pressure. See also **gas carbon arc welding, shielded carbon arc welding,** and **twin carbon arc welding**.

carbon electrode. A nonfiller metal electrode used in arc welding and cutting, consisting of a carbon or graphite rod, which may be coated with copper or other materials.

carbonizing flame. A nonstandard term for **carburizing flame.**

carburizing flame. A reducing oxyfuel gas flame in which there is an excess of fuel gas, resulting in a carbon-rich zone extending around and beyond the cone. See also **neutral flame**, **oxidizing flame**, and **reducing flame.**

carrier gas. The gas used to transport powdered material from the feeder or hopper to a thermal spraying gun or a thermal cutting torch.

cascade sequence. A combined longitudinal and cross sectional sequence in which weld beads are made in overlapping layers. See Figure A.12(C). See also **block sequence**, **continuous sequence**, and **cross-sectional sequence.**

caulking. Plastic deformation of weld and adjacent base metal surfaces by mechanical means to seal or obscure discontinuities.

caulk weld. A nonstandard term for **seal weld.**

ceramic rod flame spraying. A thermal spraying process variation in which the surfacing material is in rod form.

chain intermittent weld. An intermittent weld on both sides of a joint in which the weld increments on one side are approximately opposite those on the other side. See Figure A.12(G).

chemical flux cutting. A nonstandard term for **flux cutting.**

chill ring. A nonstandard term when used for **backing ring.**

chill time. A nonstandard term when used for **quench time.**

circular electrode, *resistance seam welding*. A rotating electrode with contacting surface at the periphery through which welding current and force are applied to the workpieces. See **resistance welding electrode.**

clad brazing sheet. A metal sheet on which one or both sides are clad with brazing filler metal. See also **clad metal.**

cladding. A surfacing variation that deposits or applies surfacing material usually to improve corrosion or heat resistance. See also **buildup**, **buttering**, and **hardfacing**.

clad metal. A laminar composite consisting of a metal or alloy, with a metal or alloy of different chemical composition applied to one or more sides by casting, drawing, rolling, surfacing, chemical deposition, or electroplating.

cluster porosity. A localized array of porosity having a random geometric distribution.

coalescence. The growing together or growth into one body of the materials being joined.

coated electrode. A nonstandard term for **covered electrode** or **lightly coated electrode**.

coating. A nonstandard term when used for **thermal spray deposit**.

coating density. A nonstandard term when used for **spray deposit density ratio**.

coextrusion welding (CEW). A solid-state welding process that produces a weld by heating to the welding temperature and forcing the workpieces through an extrusion die.

coil without support. A filler metal package consisting of a continuous length of welding wire in coil form without an internal support. It is appropriately bound to maintain its shape.

coil with support. A filler metal package consisting of a continuous length of welding wire in coil form wound on a simple cylinder without flanges.

cold crack. A crack which develops after solidification is complete.

cold lap. A nonstandard term when used for **incomplete fusion** or **overlap,** *fusion welding*.

cold soldered joint. A joint with incomplete coalescence caused by insufficient application of heat to the base metal during soldering.

cold welding (CW). A solid-state welding process in which pressure is used to produce a weld at room temperature with substantial deformation at the weld. See also **diffusion welding, forge welding**, and **hot pressure welding.**

collar. The reinforcing metal of a nonpressure thermite weld.

collaring, *thermal spraying***.** Adding a shoulder to a shaft or similar component as a protective confining wall for the thermal spray deposit.

collet, *gas tungsten arc welding, plasma arc cutting, plasma arc welding,* and *thermal spraying***.** A mechanical clamping device used to hold the electrode in position within the welding, cutting or spraying torch.

commutator-controlled welding. The making of multiple groups of resistance spot or projection welds sequentially with the same welding contactor through the use of a commutating device.

companion panel. A nonstandard term when used for **spray tab.**

complete fusion. Fusion over the entire fusion faces and between all adjoining weld beads. See also **incomplete fusion**.

complete joint penetration (CJP). A groove weld condition in which weld metal extends through the joint thickness. See Figure A.14. See also **complete joint penetration weld, incomplete joint penetration, joint penetration**, and **partial joint penetration weld.**

complete joint penetration weld. A groove weld in which weld metal extends through the joint thickness. See Figures A.14(F) and A.14(G). See also **complete joint penetration, incomplete joint penetration, joint penetration,** and **partial joint penetration weld.**

composite. A material consisting of two or more discrete materials with each material retaining its physical identity. See also **clad metal, composite electrode,** and **composite thermal spray deposit.**

composite electrode. A generic term for multicomponent filler metal electrodes in various physical forms such as stranded wires, tubes, and covered wire. See also **covered electrode, flux cored electrode, metal cored electrode**, and **stranded electrode.**

composite thermal spray deposit. A thermal spray deposit made with two or more dissimilar surfacing materials that may be formed in layers.

concave fillet weld. A fillet weld having a concave face.

concave root surface. The configuration of a groove weld exhibiting underfill at the root surface.

concavity. The maximum distance from the face of a concave fillet weld perpendicular to a line joining the weld toe.

concurrent heating. The application of supplemental heat to a structure during welding or cutting.

cone. The conical part of an oxyfuel gas flame adjacent to the tip orifice.

connection. A nonstandard term when used for a welded, brazed, or soldered joint.

constant current power source. An arc welding power source with a volt-ampere relationship yielding a small welding current change from a large arc voltage change. See also **welding power source**.

constant voltage power source. An arc welding power source with a volt-ampere relationship yielding a large welding current change from a small arc voltage change. See also **welding power source**.

constricted arc. A plasma arc column that is shaped by the constricting orifice in the nozzle of the plasma arc torch or plasma spraying gun.

constricting nozzle. A device at the exit end of a plasma arc torch or plasma spraying gun, containing the constricting orifice.

constricting orifice. The hole in the constricting nozzle of the plasma arc torch or plasma spraying gun through which the arc plasma passes.

constricting orifice diameter. See **constricting orifice**.

constricting orifice length. See **constricting orifice**.

consumable electrode. An electrode that provides filler metal.

consumable guide electroslag welding (ESW-CG). An electroslag welding process variation in which filler metal is supplied by an electrode and its guiding member.

consumable insert. Filler metal that is placed at the joint root before welding, and is intended to be completely fused into the joint root to become part of the weld.

contact resistance, *resistance welding*. Resistance to the flow of electric current between two workpieces or an electrode and a workpiece.

contact tip. A tubular component of an arc welding gun that delivers welding current to and guides a continuous electrode.

contact tip setback, *flux cored arc welding* and *gas metal arc welding*. The distance from the contact tip to the end of the gas nozzle. See also **electrode setback**.

contact tube. A nonstandard term when used for **contact tip.**

contact tube setback. A nonstandard term when used for **contact tip setback**.

continuous feed. A nonstandard term when used for **melt-in feed.**

continuous sequence. A longitudinal sequence in which each weld bead is made continuously from one end of the joint to the other. See also **backstep sequence**, **block sequence**, and **cascade sequence**.

continuous wave laser. A laser having an output that operates in a continuous rather than a pulsed mode. A laser operating with a continuous output for a period greater than 25 milliseconds is regarded as a continuous wave laser.

continuous weld. A weld that extends continuously from one end of a joint to the other. Where the joint is essentially circular, it extends completely around the joint.

convex fillet weld. A fillet weld having a convex weld face.

convexity. The maximum distance from the face of a convex fillet weld perpendicular to a line joining the weld toes.

convex root surface. The configuration of a groove weld exhibiting root reinforcement at the root surface.

cool time, *resistance welding*. The time interval between successive heat times in multiple-impulse welding or in the making of seam welds.

copper brazing. A nonstandard term when used for **brazing** with a copper filler metal.

cord, *thermal spraying*. Surfacing material in the form of a plastic tube filled with powder that has been extruded to a compact, flexible cord with characteristics similar to a wire.

cored solder. A solder wire or bar containing flux as a core.

corner-flange weld. A nonstandard term when used for an **edge weld** in a **flanged corner joint**.

corner joint. A joint between two members located approximately at right angles to each other in the form of an "L."

corona, *resistance welding*. The area sometimes surrounding the nugget of a spot weld at the faying surfaces which provides a degree of solid-state welding.

corrective lens. A lens ground to the wearer's individual corrective prescription.

corrosive flux. A flux with a residue that chemically attacks the base metal. It may be composed of inorganic salts and acids, organic salts and acids, or activated rosin.

cosmetic weld bead. A weld bead used to enhance appearance.

cosmetic weld pass. A weld pass resulting in a cosmetic weld bead.

CO_2 welding. A nonstandard term when used for **flux cored arc welding** or **gas metal arc welding** with carbon dioxide shielding gas.

covalent bond. A primary bond arising from the reduction in energy associated with overlapping half-filled orbitals of two atoms.

cover bead. A weld bead resulting from a cover pass. See Figures A.12(D) and A.12(E).

covered electrode. A composite filler metal electrode consisting of a core of a bare electrode or metal cored electrode to which a covering sufficient to provide a slag layer on the weld metal has been applied. The covering may contain materials providing such functions as shielding from the atmosphere, deoxidation, and arc stabilization, and can serve as a source of metallic additions to the weld. See also **lightly covered electrode.**

cover lens. A nonstandard term for a **cover plate.**

cover pass. A weld pass or passes resulting in the exposed layer of a multipass weld on the side from which welding was done.

cover plate. A removable pane of colorless glass, plastic-coated glass, or plastic that covers the filter plate and protects it from weld spatter, pitting, or scratching.

crack. A fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

crater. A depression in the weld face at the termination of a weld bead.

crater crack. See Figure A.16.

crater fill current. The current value during crater fill time.

crater fill time. The time interval following weld time but prior to meltback time during which arc voltage or current reach a preset value greater or less than welding values. Weld travel may or may not stop at this point.

crater fill voltage. The arc voltage value during crater fill time.

cross-sectional sequence. The order in which the weld passes of a multiple-pass weld are made with respect to the cross section of the weld. See Figures A.12(D) and A.12(E). See also **block sequence**, **cascade sequence**, and **continuous sequence.**

cross wire welding. A common variation of projection welding wherein the localization of the welding current is achieved by the intersection contact of wires, and is usually accompanied by considerable embedding of one wire into another.

crushed slag. A nonstandard term when used for **recycled slag.**

cup. A nonstandard term when used for **gas nozzle.**

cutter. See **thermal cutter.**

cutting. See **thermal cutting.**

cutting attachment. A device for converting an oxyfuel gas welding torch into an oxyfuel gas cutting torch.

cutting blowpipe. A nonstandard term for **oxyfuel gas cutting torch.**

cutting electrode. A nonfiller metal electrode used in arc cutting. See also **carbon electrode, metal electrode,** and **tungsten electrode.**

cutting head. The part of a cutting machine in which a cutting torch or tip is incorporated.

cutting nozzle. A nonstandard term for **cutting tip**.

cutting operator. See **thermal cutting operator.**

cutting tip. The part of an oxyfuel gas cutting torch from which the gases issue.

cutting torch. See **air carbon arc cutting torch, gas tungsten arc cutting torch, oxyfuel gas cutting torch**, and **plasma arc cutting torch**.

cycle. The duration of alternating current represented by the current increase from an initial value to a maximum in one direction then to a maximum in the reverse direction and its return to the original initial value.

cylinder. See **gas cylinder.**

cylinder manifold. A header for interconnection of multiple gas sources with distribution points.

D

defect. A discontinuity or discontinuities that by nature or accumulated effect render a part or product unable to meet minimum applicable acceptance standards or specifications. The term designates rejectability. See also **discontinuity** and **flaw.**

delayed crack. A nonstandard term when used for **cold crack** or **underbead crack.**

deposit. A nonstandard term when used for **thermal spray deposit**.

deposited metal, *brazing, soldering,* and *welding*. Filler metal that has been added during brazing, soldering or welding.

deposited metal, *surfacing*. Surfacing metal that has been added during surfacing.

deposition efficiency. See **arc welding deposition efficiency** and **thermal spraying deposition efficiency.**

deposition rate. The weight of material deposited in a unit of time.

deposition sequence. A nonstandard term when used for **weld pass sequence**.

deposit sequence. A nonstandard term when used for **weld pass sequence.**

depth of bevel. The perpendicular distance from the base metal surface to the root edge or the beginning of the root face. See Figure A.4.

depth of fusion. The distance that fusion extends into the base metal or previous bead from the surface melted during welding. See also **joint penetration.**

detonation flame spraying. A thermal spraying process variation in which the controlled explosion of a mixture of fuel gas, oxygen, and powdered surfacing material is utilized to melt and propel the surfacing material to the substrate.

die. A nonstandard term when used for **resistance welding die.**

die welding. A nonstandard term when used for **cold welding** and **forge welding**.

diffusion aid. A solid filler metal applied to the faying surfaces to assist in diffusion welding.

diffusion bonding. A nonstandard term for **diffusion brazing** and **diffusion welding.**

diffusion brazing (DFB). A brazing process that produces coalescence of metals by heating them to brazing temperature and by using a filler metal or an *in-situ* liquid phase. The filler metal may be distributed by capillary attraction or may be placed or formed at the faying surfaces. The filler metal is diffused with the base metal to the extent that the joint properties have been changed to approach those of the base metal. Pressure may or may not be applied.

diffusion welding (DFW). A solid-state welding process that produces a weld by the application of pressure at elevated temperature with no macroscopic deformation or relative motion of the workpieces. A solid filler metal may be inserted between the faying surfaces. See also **cold welding, diffusion aid, forge welding,** and **hot pressure welding.**

dilution. The change in chemical composition of a welding filler metal caused by the admixture of the base metal or previous weld metal in the weld bead. It is measured by the percentage of base metal or previous weld metal in the weld bead. See Figure A.13(L).

dip brazing (DB). A brazing process that uses heat from a molten chemical or metal bath. When a molten chemical is used, the bath may act as a flux. When a molten metal is used, the bath provides the filler metal. See also **metal-bath dip brazing** and **salt-bath dip brazing**.

dip feed, *gas tungsten arc welding, oxyfuel gas welding,* and *plasma arc welding*. A process variation in which filler metal is intermittently fed into the leading edge of the weld pool.

dip soldering (DS). A soldering process using the heat furnished by a molten metal bath that provides the solder filler metal. See also **wave soldering.**

dip transfer. A nonstandard term when used for **dip feed** or **short circuiting transfer.**

direct current electrode negative (DCEN). The arrangement of direct current arc welding leads in which the electrode is the negative pole and workpiece is the positive pole of the welding arc.

direct current electrode positive (DCEP). The arrangement of direct current arc welding leads in which the electrode is the positive pole and the workpiece is the negative pole of the welding arc.

direct current reverse polarity. A nonstandard term for **direct current electrode positive.**

direct current straight polarity. A nonstandard term for **direct current electrode negative.**

direct drive friction welding (FRW-DD). A variation of friction welding in which the energy required to make the weld is supplied to the welding machine through a direct motor connection for a preset period of the welding cycle. See also **inertia friction welding.**

direct welding, *resistance welding*. A resistance welding secondary circuit variation in which welding current and electrode force are applied to the workpieces by directly opposed electrodes, wheels, or conductor bars for spot, seam, or projection welding.

discontinuity. An interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics. A discontinuity is not necessarily a defect. See also **defect** and **flaw.**

doped solder. A solder containing a small amount of an element added to ensure retention of one or more characteristics of the base materials on which it is used.

double arcing. A condition in which the welding or cutting arc of a plasma arc torch does not pass through the constricting orifice but transfers to the inside surface of the nozzle. A secondary arc is simultaneously established between the outside surface of the nozzle and the workpiece.

double-bevel edge shape. A type of bevel edge shape having two prepared surfaces adjacent to opposite sides of the material.

double-bevel groove. A double-sided weld groove formed by the combination of a butting member having a double-bevel edge shape abutting a planar surface of a companion member. See Figure A.4(B).

double-bevel-groove weld. A weld in a double-bevel-groove welded from both sides. See Figure A.4(B).

double-flare-bevel groove. A double-sided weld groove formed by the combination of a butting member having a round edge shape and a planar surface of a companion member. See Figure A.6(F).

double-flare-bevel-groove weld. A weld in a double-flare-bevel groove welded from both sides. See Figure A.6(F).

double-flare-V groove. A double-sided weld groove formed by the combination of butting members having round edge shapes. See Figure A.6(G).

double-flare-V-groove weld. A weld in a double-flare-V-groove welded from both sides. See Figure A.6(G).

double-groove weld, *fusion welding*. A groove weld that is made from both sides. See Figures A.6, A.13(C), and A.13(D).

double-J edge shape. A type of edge shape having two prepared surfaces adjacent to opposite sides of the material. See Figure A.6(D).

double-J groove. A double-sided weld groove formed by the combination of a butting member having a double-J edge shape abutting a planar surface of a companion member. See Figure A.6(D).

double-J-groove weld. A weld in a double-J groove welded from both sides. See Figure A.6(D).

double-spliced butt joint. See **spliced joint.**

double-square-groove weld. A weld in a square groove welded from both sides. See Figure A.6(A).

double-U groove. A double-sided weld groove formed by the combination of butting members having double-J edge shapes. See Figure A.6(E).

double-U-groove weld. A weld in a double-U-groove welded from both sides. See Figure A.6(E).

double-V groove. A double-sided weld groove formed by the combination of butting members having double-bevel edge shapes. See Figure A.6(C).

double-V-groove weld. A weld in a double-V-groove welded from both sides. See Figure A.6(C).

double-welded joint, *fusion welding*. A joint that is welded from both sides. See Figures A.6, A.13(C), and A.13(D).

dovetailing, *thermal spraying*. A method of surface roughening involving angular undercutting to interlock the thermal spray deposit.

downhand. A nonstandard term for **flat welding position**.

downhill, *adv.* Welding with a downward progression.

downslope time. See **automatic arc welding downslope time** and **resistance welding downslope time**.

drag, *thermal cutting*. The offset distance between the actual and straight line exit points of the gas stream or cutting beam measured on the exit surface of the base metal.

drag angle. The travel angle when the electrode is pointing in a direction opposite to the progression of welding. This angle can also be used to partially define the position of guns, torches, rods, and beams. See also **backhand welding, push angle, travel angle,** and **work angle.**

drop-through. An undesirable sagging or surface irregularity, usually encountered when brazing or welding near the solidus of the base metal, caused by overheating with rapid diffusion or alloying between the filler metal and the base metal.

dross, *thermal cutting*. The remaining solidified, oxidized metallic material adhering to the workpiece adjacent to the cut surface.

drum. A filler metal package consisting of a continuous length of welding wire wound or coiled in a cylindrical container.

duty cycle. The percentage of time during a specified test period that a power source or its accessories can be operated at rated output without overheating.

dwell time, *thermal spraying*. The length of time that the surfacing material is exposed to the heat zone of the thermal spraying gun.

dwell time, *welding*. The time during which the energy source pauses at any point in each oscillation.

dynamic electrode force. The force exerted by electrodes on the workpieces during the actual welding cycle in making spot, seam, or projection welds by resistance welding. See also **static electrode force** and **theoretical electrode force.**

E

edge effect, *thermal spraying*. Loosening of the bond between the thermal spray deposit and the substrate at the edge of the thermal spray deposit.

edge-flange weld. A nonstandard term for an **edge weld** in a flanged butt joint.

edge joint. A joint between the edges of two or more parallel or nearly parallel members. See Figure A.1(E).

edge loss, *thermal spraying*. Thermal spray deposit lost as overspray beyond the edge of the workpiece.

edge preparation. The preparation of the edges of the joint members, by cutting, cleaning, plating, or other means.

edge preparation. A nonstandard term when used for **edge shape.**

edge shape. The shape of the edge of the joint member.

edge weld. A weld in an edge joint, a flanged butt joint or a flanged corner joint in which the full thickness of the members are fused.

edge weld size. The weld metal thickness measured from the weld root.

effective throat. The minimum distance from the fillet weld face, minus any convexity, and the weld root. In the case of a fillet weld combined with a groove weld, the weld root of the groove weld shall be used. See also **actual throat** and **theoretical throat.**

electric arc spraying. A nonstandard term for **arc spraying.**

electric bonding. A nonstandard term when used for **surfacing** by thermal spraying.

electric brazing. A nonstandard term for **arc brazing** and **resistance brazing.**

electrode. A component of the electrical circuit that terminates at the arc, molten conductive slag, or base metal. See **cutting electrode, tungsten electrode,** and **welding electrode.**

electrode cap. A replaceable electrode tip used for resistance spot welding.

electrode extension, *carbon arc cutting*. The length of electrode extending beyond the electrode holder or cutting torch.

electrode extension, *flux cored arc welding, electrogas welding, gas metal arc welding*, and *submerged arc welding*. The length of electrode extending beyond the end of the contact tube.

electrode extension, *gas tungsten arc welding* and *plasma arc welding*. The length of tungsten electrode extending beyond the end of the collet.

electrode force, *resistance welding*. The force applied by the electrodes to the workpieces in making spot, seam, or projection welds. See also **dynamic electrode force, static electrode force,** and **theoretical electrode force.**

electrode gap. A nonstandard term for **arc length.**

electrode holder. A device used for mechanically holding and conducting current to an electrode during welding or cutting.

electrode indentation, *resistance welding*. The depression formed on the surface of workpieces by electrodes.

electrode lead. The electrical conductor between the source of arc welding current and the electrode holder.

electrode mushrooming. The enlargement of a resistance spot or projection welding electrode tip due to heat or pressure so it resembles a mushroom in shape.

electrode pickup. Contamination of the electrode tips or wheel faces by the base metal or its coating during resistance spot, seam, or projection welding.

electrode setback. The distance the electrode is recessed behind the constricting orifice of the plasma arc torch or thermal spraying gun, measured from the outer face of the constricting nozzle. See also **contact tip setback.**

electrode skid. The sliding of a resistance welding electrode along the surface of the workpiece when making spot, seam, or projection welds.

electrode tip. The end of a resistance spot or projection welding electrode in contact with the workpiece.

electrode tip life. The number of resistance spot welds that can be made with an electrode before redressing of the electrode is required.

electrogas welding (EGW). An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool, employing approximately vertical welding progression with backing to confine the molten weld metal. The process is used with or without an externally supplied shielding gas and without the application of pressure.

electron beam braze welding (EBBW). A braze welding process variation that uses an electron beam as the heat source.

electron beam cutting (EBC). A thermal cutting process that severs metals by melting them with the heat from a concentrated beam, composed primarily of high-velocity electrons, impinging on the workpiece.

electron beam cutting operator. See **thermal cutting operator.**

electron beam gun. A device for producing and accelerating electrons. Typical components include the emitter (also called the filament or cathode) that is heated to produce electrons via thermionic emission, a cup (also called the grid or grid cup), and the anode.

electron beam gun column. The electron beam gun plus auxiliary mechanical and electrical components that may include beam alignment, focus, and deflection coils.

electron beam welding (EBW). A welding process that produces coalescence with a concentrated beam, composed primarily of high-velocity electrons, impinging on the joint. The process is used without shielding gas and without the application of pressure. See also **high vacuum electron beam welding**, **medium vacuum electron beam welding**, and **nonvacuum electron beam welding.**

electroslag welding (ESW). A welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag, which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing between the electrode and the workpieces. See also **electroslag welding electrode** and **consumable guide electroslag welding.**

electroslag welding electrode. A filler metal component of the welding circuit through which current is conducted from the electrode guiding member to the molten slag.

elongated porosity. A form of porosity having a length greater than its width that lies approximately parallel to the weld axis.

emissive electrode. A filler metal electrode consisting of a core of a bare electrode or a composite electrode to which a very light coating has been applied to produce a stable arc.

end return. A nonstandard term for **boxing.**

erosion, *brazing*. A condition caused by dissolution of the base metal by molten filler metal resulting in a reduction in the thickness of the base metal.

exhaust booth. A mechanically ventilated, semienclosed area in which an air flow across the work area is used to remove fumes, gases, and solid particles.

exothermic braze welding (EXBW). A braze welding process variation that uses an exothermic chemical reaction between a metal oxide and a metal or inorganic nonmetal as the heat source, with a reaction product as the filler metal.

exothermic brazing (EXB). A brazing process using an exothermic chemical reaction between a metal oxide and a metal or inorganic nonmetal as the heat source, with filler metal preplaced in the joint.

explosion welding (EXW). A solid-state welding process that produces a weld by high velocity impact of the workpieces as the result of controlled detonation.

expulsion. The forceful ejection of molten metal from a resistance spot, seam, or projection weld usually at the faying surface. See also **surface expulsion.**

expulsion point, *resistance welding*. The amount of welding current above which expulsion occurs for a given set of welding conditions.

extension, *resistance welding*. The distance the workpiece or electrode projects from a welding die, clamp, chuck, or holder.

F

face bend test. A test in which the weld face is on the convex surface of a specified bend radius.

face crack. See Figure A.16.

face feed. The application of filler metal to the heated joint.

face of weld. See **weld face.**

face reinforcement. Weld reinforcement on the side of the joint from which welding was done. See Figures A.13(A) and A.13(C). See also **root reinforcement.**

face shield. A device positioned in front of the eyes and over all or a portion of the face to protect the eyes and face. See also **hand shield** and **welding helmet.**

faying surface. The mating surface of a member that is in contact with or in close proximity to another member to which it is to be joined.

feather. See **acetylene feather.**

feed rate, *thermal spraying*. A nonstandard term for **spraying rate.**

Ferrite Number (FN). An arbitrary, standardized value designating the ferrite content of an austenitic or duplex ferrite-austenitic stainless steel weld metal based on its magnetic properties. The term is always a proper noun and is always capitalized. **Ferrite Number** should not be confused with **percent ferrite**; the two are not equivalent.

ferrule, *arc stud welding*. A ceramic device that surrounds the stud base to contain the molten metal and shield the arc.

field weld. A weld made at a location other than a shop or the place of initial construction.

fill bead. A nonstandard term when used for **intermediate weld bead.**

filler. See **joint filler.**

filler bead. A nonstandard term when used for **intermediate weld bead.**

filler material. The material to be added in making a brazed, soldered or welded joint. See also **brazing filler metal, consumable insert, diffusion aid, filler metal, solder, welding electrode, welding filler metal, welding rod,** and **welding wire.**

filler metal. The metal or alloy to be added in making a brazed, soldered or welded joint. See also **brazing filler metal, consumable insert, diffusion aid, filler material, filler metal powder, solder, welding electrode, welding filler metal, welding rod,** and **welding wire.**

filler metal powder. Filler metal in particle form.

filler metal start delay time. The time interval from arc initiation to the start of filler metal feeding.

filler metal stop delay time. The time delay interval from beginning of downslope time to the stop of filler metal feeding.

filler pass. A nonstandard term when used for **intermediate weld pass.**

filler wire. A nonstandard term for **welding wire.**

fillet weld. A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap joint, T-joint, or corner joint. See Figures A.12(G), A.12(H), A.13(E), and A.13(J).

fillet weld break test. A test in which the specimen is loaded so that the weld root is in tension.

fillet weld leg. The distance from the joint root to the toe of the fillet weld. See Figure A.13(E).

fillet weld size. For equal leg fillet welds, the leg lengths of the largest isosceles right triangle that can be inscribed within the fillet weld cross section. For unequal leg fillet welds, the leg lengths of the largest right triangle that can be inscribed within the fillet weld cross section.

fillet weld throat. See **actual throat, effective throat,** and **theoretical throat.**

fill pass. A nonstandard term when used for **intermediate weld pass.**

fill weld. A fusion weld made with filler metal.

filter glass. A nonstandard term for **filter plate.**

filter lens. A nonstandard term for a round **filter plate.**

filter plate. An optical material that protects the eyes against excessive ultraviolet, infrared, and visible radiation.

final current. The current after downslope but prior to current shut-off.

final taper current. The current at the end of the taper interval prior to downslope.

fines. Particles of flux or filler metal having a size smaller than a particular mesh size.

firecracker welding. A shielded metal arc welding process variation that uses a length of covered electrode placed along the joint in contact with the workpieces during welding. The stationary electrode is consumed as the arc travels the length of the electrode. This is an obsolete or seldom used process variation.

fisheye. A discontinuity, attributed to the presence of hydrogen in the weld, observed on the fracture surface of a weld in steel that consists of a small pore or inclusion surrounded by an approximately round, bright area.

fit, *v.* The act of bringing together the workpiece(s) in preparation for welding.

fitter. One who fits the workpiece(s) in preparation for welding.

fitup. The resultant condition of the workpiece(s) that have been brought together for welding.

5F. A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately horizontal, in which the weld is made in the horizontal, vertical, and overhead welding positions. The pipe remains fixed until the welding of the joint is complete. See Figure A.11(E).

5G. A welding test position designation for a circumferential groove weld applied to a joint in a pipe with its axis horizontal, in which the weld is made in the flat, vertical, and overhead welding positions. The pipe remains fixed until the welding of the joint is complete. See Figure A.10(C).

fixture. A device designed to hold and maintain parts in proper relation to each other.

flame. See **carburizing flame**, **neutral flame**, **oxidizing flame**, and **reducing flame**.

flame cutting. A nonstandard term for **oxygen cutting**.

flame propagation rate. The speed at which flame travels through a mixture of gases.

flame sprayer. See **thermal sprayer**.

flame spraying (FLSP). A thermal spraying process in which an oxyfuel gas flame is the source of heat for melting the surfacing material. Compressed gas may or may not be used for atomizing and propelling the surfacing material to the substrate.

flame spraying operator. See **thermal spraying operator**.

flanged butt joint. A form of a butt joint in which at least one of the members has a flanged edge shape at the joint.

flanged corner joint. A form of a corner joint in which the butting member has a flanged edge shape at the joint, and an edge weld is applicable.

flanged edge joint. A form of an edge joint in which at least one of the members has a flanged edge shape at the joint.

flanged edge shape. A type of edge shape produced by forming the member.

flanged joint. A form of one of the five basic joint types in which at least one of the joint members has a flanged edge shape at the weld joint.

flanged lap joint. A form of a lap joint in which at least one of the members has a flanged edge shape at the joint, and an edge weld is not applicable.

flanged T-joint. A form of a T-joint in which the butting member has a flanged edge shape at the joint, and an edge weld is not applicable.

flange weld. A nonstandard term for a **weld** in a flanged joint.

flare-bevel-groove weld. A weld in the groove formed between a joint member with a curved surface and another with a planar surface. See Figures A.5(H), A.6(F), and A.14(H).

flare-groove weld. A weld in the groove formed between a joint member with a curved surface and another with a planar surface, or between two joint members with curved surfaces. See Figures A.5(H), A.5(I), A.6(F), and A.6(G). See also **flare-bevel-groove weld** and **flare-V-groove weld.**

flare-V-groove weld. A weld in a groove formed by two members with curved surfaces. See Figures A.5(I) and A.6(G).

flash. Material that is expelled from a flash weld prior to the upset portion of the welding cycle.

flashback. A recession of the flame into or back of the mixing chamber of the oxyfuel gas torch or flame spraying gun.

flashback arrester. A device to limit damage from a flashback by preventing propagation of the flame front beyond the location of the arrester.

flash butt welding. A nonstandard term for **flash welding.**

flash coat. A thin coating usually less than 0.05 mm (0.002 in.) in thickness.

flashing action. The phenomenon in flash welding in which points of contact formed by light pressure across faying surfaces are melted and explosively ejected because of the extremely high current density at contact points.

flash off time. A nonstandard term for **flash time.**

flashover, *electron beam welding*. Undesirable arcing occurring within the electron beam gun.

flash time. The duration of flashing action during flash welding.

flash welding (FW). A resistance welding process that produces a weld at the faying surfaces of a butt joint by a flashing action and by the application of pressure after heating is substantially completed. The flashing action, caused by the very high current densities at small contact points between the workpieces, forcibly expels the material from the joint as the workpieces are slowly moved together. The weld is completed by a rapid upsetting of the workpieces.

flat position. See **flat welding position.**

flat welding position. The welding position used to weld from the upper side of the joint at a point where the weld axis is approximately horizontal, and the weld face lies in an approximately horizontal plane. See Figures A.8, A.9, A.10(A), and A.11(A).

flaw. An undesirable discontinuity. See also **defect.**

flood cooling, *resistance seam welding*. The application of liquid coolant directly on the work and the contacting electrodes.

flowability. The ability of molten filler metal to flow or spread over a metal surface.

flow brazing (FLB). A braze welding process that uses heat from molten nonferrous filler metal poured over the joint until brazing temperature is attained. This is an obsolete or seldom used process. See also **flow welding** and **wave soldering.**

flow brightening, *soldering*. Fusion of a metallic coating on a base metal.

flow welding (FLOW). A braze welding process variation that uses molten filler metal poured over the fusion faces as the heat source. This is an obsolete or seldom used process. See also **flow brazing**.

flux. A material used to hinder or prevent the formation of oxides and other undesirable substances in molten metal and on solid metal surfaces, and to dissolve or otherwise facilitate the removal of such substances. See also **active flux, neutral flux**, and **slag.**

flux cored arc welding (FCAW). An arc welding process that uses 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. See also **flux cored electrode, gas shielded flux cored arc welding,** and **self-shielded flux cored arc welding**.

flux cored electrode. A composite tubular filler metal electrode consisting of a metal sheath and a core of various powdered materials, producing an extensive slag cover on the face of a weld bead.

flux cover, *metal bath dip brazing* and *dip soldering*. A layer of molten flux over the molten filler metal bath.

flux cutting (OC-F). An oxygen cutting process that uses heat from an oxyfuel gas flame, with a flux in the flame to aid cutting.

flux oxygen cutting. A nonstandard term for **flux cutting.**

focal point. A nonstandard term for **focal spot.**

focal spot, *electron beam welding and cutting,* and *laser beam welding and cutting*. A location at which the beam has the most concentrated energy and the smallest cross-sectional area.

follow-up, *resistance welding*. The ability of the moveable electrode to maintain proper electrode force and contact with the workpiece as metal movement occurs, especially in projection welding.

forehand welding. A welding technique in which the welding torch or gun is directed toward the progress of welding. See also **push angle, travel angle**, and **work angle.**

forge-delay time, *resistance welding*. The time elapsing between a preselected point in the welding cycle and the initiation of the forging force.

forge force. A compressive force applied to the weld after the heating portion of the welding cycle is essentially complete.

forge welding (FOW). A solid-state welding process that produces a weld by heating the workpieces to welding temperature and applying blows sufficient to cause permanent deformation at the faying surfaces. See also **cold welding, diffusion welding,** and **hot pressure welding.**

forging speed, *friction welding*. The relative velocity of the workpieces at the instant the forge force is applied.

4F, *plate*. A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the overhead welding position.

4F, *pipe*. A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis vertical, in which the weld is made in the overhead welding position. See Figure A.11(D).

4G. A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the overhead welding position.

friction soldering. A nonstandard term for **abrasion soldering**.

friction speed, *friction welding*. The relative velocity of the workpieces at the time of initial contact.

friction stir welding (FSW). A variation of friction welding that produces a weld between two butting workpieces by the friction heating and plastic material displacement caused by a high speed rotating tool that traverses along the weld joint.

friction upset distance. The decrease in length of workpieces during the time of friction welding force application.

friction welding (FRW). A solid-state welding process that produces a weld under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces. See also **direct drive friction welding**, **friction stir welding**, and **inertia friction welding.**

friction welding force. The compressive force applied to the faying surfaces during the time there is relative movement between the workpieces from the start of welding until the application of the forge force.

fuel gas. A gas such as acetylene, natural gas, hydrogen, propane, stabilized methylacetylene propadiene, and other fuels normally used with oxygen in one of the oxyfuel processes and for heating.

full fillet weld. A fillet weld equal in size to the thickness of the thinner member joined.

full penetration. A nonstandard term for **complete joint penetration**.

furnace brazing (FB). A brazing process in which the workpieces are placed in a furnace and heated to the brazing temperature.

furnace soldering (FS). A soldering process in which the workpieces are placed in a furnace and heated to the soldering temperature.

fused flux, *submerged arc welding*. A granular flux produced by mixing the ingredients followed by melting, cooling to the solid state and processing to produce the desired particle size. See also **agglomerated flux** and **bonded flux.**

fused thermal spray deposit. A self-fluxing thermal spray deposit that is subsequently heated to coalescence within itself and with the substrate using the spray-fuse thermal spraying technique.

fused zone. A nonstandard term for **fusion zone.**

fusing. A nonstandard term for **fusion.**

fusion, *fusion welding*. The melting together of filler metal and base metal, or of base metal only, to produce a weld. See also **depth of fusion.**

fusion face. A surface of the base metal that has been melted during welding.

fusion line. A nonstandard term for **weld interface.**

fusion welding. Any welding process that uses fusion of the base metal to make the weld. See Figures A.17, A.19, and A.20.

fusion zone. The area of base metal melted as determined on the cross section of a weld.

G

gap. A nonstandard term when used for **arc length, joint clearance**, and **root opening.**

gas brazing. A nonstandard term for **torch brazing.**

gas carbon arc welding (CAW-G). A carbon arc welding process variation that uses a shielding gas. This is an obsolete or seldom used process.

gas cup. A nonstandard term for **gas nozzle.**

gas cutter. A nonstandard term for **oxygen cutter.**

gas cutting. A nonstandard term for **oxygen cutting.**

gas cylinder. A portable container used for transportation and storage of compressed gas.

gas gouging. A nonstandard term for **oxygen gouging.**

gas laser. A laser in which the lasing medium is a gas.

gas lens. One or more fine mesh screens located in the gas nozzle to produce a stable stream of shielding gas. This device is primarily used for gas tungsten arc welding.

gas metal arc cutting (GMAC). An arc cutting process that uses a continuous consumable electrode and a shielding gas.

gas metal arc welding (GMAW). An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of pressure. See also **pulsed gas metal arc welding** and **short circuit gas metal arc welding.**

gas nozzle. A device at the exit end of the torch or gun that directs shielding gas.

gas pocket. A nonstandard term for **porosity.**

gas regulator. A device for controlling the delivery of gas at some substantially constant pressure.

gas shielded arc welding. A group of processes including **electrogas welding, flux cored arc welding, gas metal arc welding, gas tungsten arc welding,** and **plasma arc welding.**

gas shielded flux cored arc welding (FCAW-G). A flux cored arc welding process variation in which shielding gas is supplied through the gas nozzle, in addition to that obtained from the flux within the electrode.

gas torch. A nonstandard term when used for **cutting torch** and **welding torch.**

gas tungsten arc cutting (GTAC). An arc cutting process that uses a single tungsten electrode with gas shielding.

gas tungsten arc cutting torch. A device used to transfer current to a fixed cutting electrode, position the electrode, and direct the flow of shielding gas.

gas tungsten arc welding (GTAW). An arc welding process that uses an arc between a tungsten electrode (nonconsumable) and the weld pool. The process is used with shielding gas and without the application of pressure. See also **hot wire welding** and **pulsed gas tungsten arc welding.**

gas tungsten arc welding torch. A device used to transfer current to a fixed welding electrode, position the electrode, and direct the flow of shielding gas.

gas welding. A nonstandard term for **oxyfuel gas welding.**

getter. A material, such as hot titanium or zirconium, used to purify vacuum or inert gas atmospheres by absorbing or reacting with impurities, which if not removed, would interfere with the process or excessively contaminate the workpieces, product, equipment, or tooling.

globular arc. A nonstandard term for **globular transfer.**

globular transfer, *gas metal arc welding*. The transfer of molten metal in large drops from a consumable electrode across the arc. See also **short circuiting transfer** and **spray transfer.**

goggles. Protective glasses equipped with filter plates set in a frame that fits snugly against the face and used primarily with oxyfuel gas processes.

gouging. See **thermal gouging.**

governing metal thickness, *resistance welding*. The thickness of the sheet on which the required weld nugget size and depth of fusion is based.

gradated thermal spray deposit. A composite thermal spray deposit composed of mixed materials in successive layers that progressively change in composition from the substrate to the surface of the thermal spray deposit.

groove and rotary roughening, *thermal spraying*. A method of surface preparation in which grooves are made and the original surface is roughened and spread. See also **knurling, rotary roughening,** and **threading and knurling.**

groove angle. The included angle between the groove faces of a weld groove. See Figure A.4. See also **bevel angle.**

groove face. Any surface in a weld groove prior to welding. See Figure A.3. See also **bevel face** and **root face.**

groove radius. A nonstandard term when used for **bevel radius.**

groove weld. A weld in a weld groove on a workpiece surface, between workpiece edges, between workpiece surfaces, or between workpiece edges and surfaces. See Figures A.5 and A.6.

groove weld size. The joint penetration of a groove weld. See Figure A.14.

ground clamp. A nonstandard and incorrect term for **workpiece connection.**

ground connection. An electrical connection of the welding machine frame to the earth for safety. See also **workpiece connection** and **workpiece lead.**

ground lead. A nonstandard and incorrect term for **workpiece lead.**

gun. See **arc cutting gun, arc welding gun, electron beam gun, resistance welding gun, soldering gun,** and **thermal spraying gun.**

gun extension. The extension tube attached in front of the thermal spraying gun to permit spraying within confined areas or deep recesses.

H

hammering, *resistance spot welding.* Excessive electrode impact on the surface of the workpiece at the start of the welding cycle.

hammer welding. A nonstandard term for **cold welding** and **forge welding.**

hand shield. A protective device used in arc cutting, arc welding and thermal spraying, for shielding the eyes, face, and neck. It is equipped with a filter plate and is designed to be held by hand.

hardfacing. A surfacing variation in which surfacing material is deposited to reduce wear. See also **buildup, buttering,** and **cladding.**

hard solder. A nonstandard term for **brazing filler metal.**

hard surfacing. A nonstandard term for **hardfacing.**

head. See **cutting head** and **welding head.**

heat-affected zone (HAZ). The portion of the base metal whose mechanical properties or microstructure have been altered by the heat of welding, brazing, soldering, or thermal cutting. See Figure A.13(G).

heat-affected zone crack. A crack occurring in the heat-affected zone. See Figure A.16.

heat balance. The various material, joint, and welding conditions that determine the welding heat pattern in the joint.

heating gate. The opening in a thermite mold through which the workpieces are preheated.

heating torch. A device for directing the heating flame produced by the controlled combustion of fuel gases.

heat input, *arc spot welding, projection welding,* and *resistance spot welding.* Energy supplied by the welding process to the workpiece to produce a spot weld. See also **heat input rate.**

heat input, *arc welding.* The energy supplied by the welding arc to the workpiece.

heat input rate, *arc welding.* The energy per unit length of weld supplied by the welding arc to the workpiece. See also **heat input.**

heat time. The duration of any one impulse in multiple impulse welding or resistance seam welding.

helmet. See **welding helmet.**

hermetically sealed container. A container that has been closed in a manner that provides a nonpermeable barrier to the passage of air or gas in either direction.

high energy beam cutting (HEBC). A group of thermal cutting processes that severs or removes material by localized melting, burning or vaporizing of the workpieces using beams having high energy densities. See also **electron beam cutting** and **laser beam cutting.**

high-frequency resistance welding. A group of resistance welding process variations that use high-frequency welding current to concentrate the welding heat at the desired location. See also **high-frequency seam welding** and **high-frequency upset welding.**

high-frequency seam welding (RSEW-HF). A resistance seam welding process variation in which high-frequency welding current is supplied through electrodes into the workpieces. See also **high-frequency resistance welding** and **induction seam welding.**

high-frequency upset welding (UW-HF). An upset welding process variation in which high-frequency welding current is supplied through electrodes into the workpieces. See also **high-frequency resistance welding** and **induction upset welding.**

high-low. A nonstandard term for **weld joint mismatch.**

high pulse current, *pulsed power welding*. The current during the high pulse time that produces the high heat level.

high pulse time, *pulsed power welding*. The duration of the high pulse current.

high vacuum electron beam welding (EBW-HV). An electron beam welding process variation in which welding is accomplished at a pressure of 10^{-4} to 10^{-1} pascals (approximately 10^{-6} to 10^{-3} torr).

high velocity oxyfuel spraying (HVOF). A thermal spraying process using a high pressure oxyfuel mixture to heat and propel a powdered surfacing material to a substrate.

hold time, *projection welding, resistance seam welding and resistance spot welding*. The duration of force application at the point of welding after the last pulse ceases.

hollow bead. A nonstandard term when used for **elongated porosity** occurring in a root bead.

hood. A nonstandard term for **welding helmet.**

horizontal fixed position, *pipe*. A nonstandard term when used for **multiple welding position** and **5G.**

horizontal position. See **horizontal welding position.**

horizontal rolled position, *pipe*. A nonstandard term when used for the **flat welding position** and **1G.**

horizontal welding position, *fillet weld*. The welding position in which the weld is on the upper side of an approximately horizontal surface and against an approximately vertical surface. See Figures A.9, A.11(B), and A.11(C).

horizontal welding position, *groove weld*. The welding position in which the weld face lies in an approximately vertical plane and the weld axis at the point of welding is approximately horizontal. See Figures A.8 and A.10(B).

horn. An extension of the arm of a resistance welding machine that transmits the electrode force, usually conducts the welding current, and may support the workpiece.

horn spacing. A nonstandard term for **throat height.**

hot crack. A crack formed at temperatures near the completion of solidification.

hot isostatic pressure welding (HIPW). A diffusion welding process variation that produces coalescence of metals by heating and applying hot inert gas under pressure.

hot pass, *pipe*. A nonstandard term when used for the **weld pass** subsequent to the root pass.

hot pressure welding (HPW). A solid-state welding process that produces a weld with heat and application of pressure sufficient to produce macro deformation of the workpieces. See also **cold welding, diffusion welding,** and **forge welding.**

hot start current. A very brief current pulse at arc initiation to stabilize the arc quickly.

hot wire welding. A variation of a fusion welding process in which a filler metal wire is resistance heated by current flowing through the wire as it is fed into the weld pool.

hydrogen brazing. A nonstandard term when used for **brazing** in a hydrogen atmosphere.

hydromatic welding. A nonstandard term for **pressure-controlled resistance welding.**

I

impulse, *resistance welding*. A group of pulses occurring on a regular frequency separated only by an interpulse time.

inclined position. A nonstandard term when used for the **multiple welding position** and **6G.**

inclined position with restriction ring. A nonstandard term when used for the **multiple welding position** and **6GR.**

included angle. A nonstandard term when used for **groove angle.**

inclusion. Entrapped foreign solid material, such as slag, flux, tungsten, or oxide.

incomplete fusion (IF). A weld discontinuity in which fusion did not occur between weld metal and fusion faces or adjoining weld beads. See also **complete fusion.**

incomplete joint penetration (IJP). A joint root condition in a groove weld in which weld metal does not extend through the joint thickness. See Figure A.14.

See also **complete joint penetration, complete joint penetration weld, joint penetration**, and **partial joint penetration weld**.

indentation, *projection welding, resistance seam welding,* and *resistance spot welding.* The depression on the exterior surface of the workpieces.

indirect welding. A resistance welding secondary circuit variation in which the welding current flows through the workpieces in locations away from, as well as at, the welds for resistance spot, seam, or projection welding.

induction brazing (IB). A brazing process that uses heat from the resistance of the workpieces to induced electric current.

induction seam welding (RSEW-I). A resistance seam welding process variation in which high-frequency welding current is induced in the workpieces. See also **high-frequency resistance welding** and **high-frequency seam welding.**

induction soldering (IS). A soldering process in which the heat required is obtained from the resistance of the workpieces to induced electric current.

induction upset welding (UW-I). An upset welding process variation in which high-frequency welding current is induced in the workpieces. See also **high-frequency resistance welding** and **high-frequency upset welding.**

induction welding (IW). A welding process that produces coalescence of metals by the heat obtained from the resistance of the workpieces to the flow of induced high-frequency welding current with or without the application of pressure. The effect of the high-frequency welding current is to concentrate the welding heat at the desired location.

induction work coil. The inductor used when welding, brazing, or soldering with induction heating equipment.

inert gas. A gas that normally does not combine chemically with materials. See also **protective atmosphere**.

inert gas metal arc welding. A nonstandard term for **gas metal arc welding.**

inert gas tungsten arc welding. A nonstandard term for **gas tungsten arc welding.**

inertia friction welding (FRW-I). A variation of friction welding in which the energy required to make the weld is supplied primarily by the stored rotational kinetic energy of the welding machine. See also **direct drive friction welding.**

infrared brazing (IRB). A brazing process that uses heat from infrared radiation.

infrared radiation. Electromagnetic energy with wave lengths from 770 to 12 000 nanometers.

infrared soldering (IRS). A soldering process in which the heat required is furnished by infrared radiation.

initial current. The current after starting, but before establishment of welding current.

insulating nozzle, *self-shielded flux cored arc welding.* A device at the exit end of the welding gun that protects the contact tube from spatter and may increase the electrode extension while maintaining a shorter stickout.

interface. See **braze interface, solder interface, thermal spray deposit interface**, and **weld interface**.

intergranular penetration. The penetration of a filler metal along the grain boundaries of a base metal.

intermediate flux. A soldering flux with a residue that generally does not attack the base metal. The original composition may be corrosive.

intermediate weld bead. A weld bead resulting from an intermediate weld pass.

intermediate weld pass. A single progression of welding along a joint subsequent to the root pass(es) and prior to the cover pass(es).

intermittent weld. A weld in which continuity is interrupted by recurring unwelded spaces. See Figures A.12(G), A.12(H), and A.12(I).

interpass temperature, *thermal spraying*. In multipass thermal spraying, the temperature of the thermal spray area between thermal spray passes.

interpass temperature, *welding*. In a multipass weld, the temperature of the weld area between weld passes.

interpulse time, *resistance welding*. The time between successive pulses of current within the same impulse.

interrupted spot welding. A nonstandard term when used for **multiple-impulse welding**.

ionic bond. A primary bond arising from the electrostatic attraction between two oppositely charged ions.

iron soldering (INS). A soldering process in which the heat required is obtained from a soldering iron.

J

J-edge shape. An edge shape formed by the combination of a bevel with a bevel radius.

J-groove weld. A type of groove weld. See Figures A.5(F) and A.6(D).

joining. Any process used for connecting materials. See Figures A.17, A.18, A.19, A.20, A.21, and A.22.

joint. The junction of members or the edges of members that are to be joined or have been joined. See Figure A.1.

joint brazing procedure. The materials, detailed methods, and practices employed in the brazing of a particular joint.

joint buildup sequence. A nonstandard term for **cross-sectional sequence**.

joint clearance, *brazing and soldering*. The distance between the faying surfaces of a joint.

joint design. The shape, dimensions, and configuration of the joint.

joint efficiency. The ratio of strength of a joint to the strength of the base metal, expressed in percent.

joint filler. A metal plate inserted between the splice member and thinner joint member to accommodate joint members of dissimilar thickness in a spliced butt joint.

joint geometry. The shape, dimensions, and configuration of a joint prior to welding.

joint opening. A nonstandard term for **root opening**.

joint penetration. The distance the weld metal extends from the weld face into a joint, exclusive of weld reinforcement. See Figure A.14. See also **groove weld size**.

joint recognition. A function of an adaptive control that determines changes in joint geometry during welding and directs the welding equipment to take appropriate action. See also **joint tracking** and **weld recognition**.

joint root. That portion of a joint to be welded where the members approach closest to each other. In cross section, the joint root may be either a point, a line, or an area. See Figure A.2.

joint spacer. A metal part, such as a strip, bar, or ring, inserted in the joint root to serve as a backing and to maintain the root opening during welding. See Figure A.13(F).

joint tracking. A function of an adaptive control that determines changes in joint location during welding and directs the welding machine to take appropriate action. See also **joint recognition** and **weld recognition.**

joint type. A weld joint classification based on the relative orientation of the members being joined. The five basic joint types are: butt, corner, edge, lap, and T. See Figure A.1.

joint welding sequence. See **welding sequence.**

K

kerf. The gap produced by a cutting process.

keyhole welding. A technique in which a concentrated heat source penetrates partially or completely through a workpiece, forming a hole (keyhole) at the leading edge of the weld pool. As the heat source progresses, the molten metal fills in behind the hole to form the weld bead.

keying. A nonstandard term for **mechanical bond.**

knee. The supporting structure of the lower arm in a resistance welding machine.

knurling, *thermal spraying*. A method of surface roughening in which the surface is upset with a knurling tool. See also **groove and rotary roughening**, **rotary roughening**, and **threading and knurling.**

L

lack of fusion. A. nonstandard term for **incomplete fusion**.

lack of penetration. A nonstandard term for **incomplete joint penetration**.

lamellar tear. A subsurface terrace and step-like crack in the base metal with a basic orientation parallel to the wrought surface caused by tensile stresses in the through-thickness direction of the base metals weakened by the presence of small dispersed, planar shaped, nonmetallic inclusions parallel to the metal surface. See Figure A.16.

lamination. A type of discontinuity with separation or weakness generally aligned parallel to the worked surface of a metal.

lance. See **oxygen lance** and **oxygen lance cutting**.

land. A nonstandard term for **root face**.

lap joint. A joint between two overlapping members in parallel planes. See Figures A.1(D) and A.2(D).

laser. A device that produces a concentrated coherent light beam by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for *light amplification by stimulated emission of radiation*.

laser beam air cutting (LBC-A). A laser beam cutting process variation that melts the workpiece and uses an air jet to remove molten and vaporized material.

laser beam braze welding (LBBW). A braze welding process variation that uses a laser beam as the heat source.

laser beam cutting (LBC). A thermal cutting process that severs metal by locally melting or vaporizing with the heat from a laser beam. The process is used with or without assist gas to aid the removal of molten and vaporized material. See also **laser beam air cutting, laser beam evaporative cutting, laser beam inert gas cutting,** and **laser beam oxygen cutting.**

laser beam cutting operator. See **thermal cutting operator.**

laser beam diameter. The diameter of a laser beam circular cross section at a specified location along the laser beam axis.

laser beam evaporative cutting (LBC-EV). A laser beam cutting process variation that vaporizes the workpiece, with or without an assist gas, typically inert gas, to aid the removal of vaporized material.

laser beam expander. A combination of optical elements that will increase the diameter of a laser beam.

laser beam inert gas cutting (LBC-IG). A laser beam cutting process variation that melts the workpiece and uses an inert assist gas to remove molten and vaporized material.

laser beam oxygen cutting (LBC-O). A laser beam cutting process variation that uses the heat from the chemical reaction between oxygen and the base metal at elevated temperatures. The necessary temperature is maintained with a laser beam.

laser beam splitter. An optical device that uses controlled reflection to produce two beams from a single incident beam.

laser beam welding (LBW). A welding process that produces coalescence with the heat from a laser beam impinging on the joint.

lasing gas. A gaseous lasing medium.

lasing medium. A material that emits coherent radiation by virtue of stimulated electronic or molecular transitions to lower energy.

layer. A stratum of weld metal consisting of one or more weld beads. See Figures A.12(D) and A.12(E).

layer level wound. A nonstandard term for **level wound.**

layer wound. A nonstandard term for **level wound.**

lead angle. A nonstandard term for **travel angle**.

lead burning. A nonstandard term when used for the welding of lead.

leg of a fillet weld. See **fillet weld leg.**

lens. See **filter lens.**

level wound. Spooled or coiled filler metal that has been wound in distinct layers such that adjacent turns touch. See also **random wound.**

lightly coated electrode. A filler metal electrode consisting of a metal wire with a light coating applied subsequent to the drawing operation, primarily for stabilizing the arc. See also **covered electrode**.

linear discontinuity. A discontinuity with a length that is substantially greater than its width.

linear indication. A test result in which a discontinuity in the material being tested is displayed as a linear or aligned array.

linear porosity. A nonstandard term when used for **aligned porosity.**

liquation. The partial melting of compositional heterogeneities such as banding or inclusion stringers in heated base metal or heat-affected zones.

liquidus. The lowest temperature at which a metal or an alloy is completely liquid.

local preheating. Preheating a specific portion of a structure.

local stress relief heat treatment. Stress relief heat treatment of a specific portion of a structure.

locked-up stress. A nonstandard term for **residual stress.**

long electrode extension, *electrogas welding, flux cored arc welding, gas metal arc welding,* and *submerged arc welding.* An increased length of electrode extension for the purpose of increasing electrical resistance to assure enhanced flux activation to provide adequate shielding (FCAW-S) or increased weld deposition rate.

longitudinal bend specimen. See **longitudinal weld test specimen.**

longitudinal crack. A crack with its major axis orientation approximately parallel to the weld axis. See Figure A.16.

longitudinal sequence. The order in which the weld passes of a continuous weld are made with respect to its length. See also **backstep sequence, block sequence, cascade sequence, continuous sequence,** and **random sequence.**

longitudinal tension specimen. See **longitudinal weld test specimen.**

longitudinal weld test specimen. A weld test specimen with its major axis parallel to the weld axis. See also **transverse weld test specimen.**

low pulse current, *pulsed power welding.* The current during the low pulse time that produces the low heat level.

low pulse time, *pulsed power welding.* The duration of the low current pulse.

M

machine. A nonstandard term when used for **mechanized.**

machine welding. A nonstandard term when used for **mechanized welding.**

macroetch test. A test in which a specimen is prepared with a fine finish, etched, and examined using no magnification or low magnification.

macroexamination. A metallographic examination in which a surface is examined using no magnification or low magnification.

magnetically impelled arc welding (MIAW). An arc welding process in which an arc is created between the butted ends of tubes and propelled around the weld joint by a magnetic field, followed by an upsetting operation.

manifold. See **cylinder manifold.**

manual, *adj.* Pertaining to the control of a process with the torch, gun, or electrode holder held and manipulated by hand. Accessory equipment, such as part motion devices and manually controlled material feeders may be used. See also **adaptive control, automatic, mechanized, robotic,** and **semiautomatic.**

manual brazing. See **manual welding.**

manual soldering. See **manual welding.**

manual thermal cutting. See **manual welding.**

manual thermal spraying. See **manual welding.**

manual welding. Welding with the torch, gun, or electrode holder held and manipulated by hand. Accessory equipment, such as part motion devices and manually controlled filler material feeders may be used. Variations of this term are **manual brazing, manual soldering, manual thermal cutting,** and **manual thermal spraying.** See also **adaptive control welding, automatic welding, mechanized welding, robotic welding,** and **semiautomatic welding.**

mash resistance seam welding. A nonstandard term for **mash seam welding.**

mash seam welding (RSEW-MS). A resistance seam welding process variation that makes a lap joint primarily by high-temperature plastic working and diffusion as opposed to melting and solidification. The joint thickness after welding is less than the original assembled thickness.

mask, *thermal spraying*. A device for protecting a substrate surface from the effects of blasting or adherence of a thermal spray deposit.

mechanical bond, *thermal spraying*. The adherence of a thermal spray deposit to a roughened surface by the mechanism of particle interlocking.

mechanically mixed flux, *submerged arc welding*. A flux produced by intentionally mixing two or more types of fluxes.

mechanized, *adj*. Pertaining to the control of a process with equipment that requires manual adjustment of the equipment controls in response to visual observation of the operation, with the torch, gun, wire guide assembly, or electrode holder held by a mechanical device. See also **adaptive control, automatic, manual, robotic,** and **semiautomatic**.

mechanized brazing. See **mechanized welding.**

mechanized soldering. See **mechanized welding.**

mechanized thermal cutting. See **mechanized welding.**

mechanized thermal spraying. See **mechanized welding.**

mechanized welding. Welding with equipment that requires manual adjustment of the equipment controls in response to visual observation of the welding, with the torch, gun, or electrode holder held by a mechanical device. Variations of this term are **mechanized brazing, mechanized soldering, mechanized thermal cutting,** and **mechanized thermal spraying.** See also **adaptive control welding, automatic welding, manual welding, robotic welding,** and **semiautomatic welding.**

medium vacuum electron beam welding (EBW-MV). An electron beam welding process variation in which welding is accomplished at a pressure of 10^{-1} to 3×10^{3} pascals (approximately 10^{-3} to 25 torr).

meltback time. The time interval at the end of crater fill time to arc outage during which electrode feed is stopped.

melt-in feed, *gas tungsten arc welding, oxyfuel gas welding,* and *plasma arc welding*. A process variation in which filler metal is preplaced or continuously fed into the leading edge of the weld pool.

melting range. The temperature range between solidus and liquidus.

melting rate. The weight or length of electrode, wire, rod, powder melted in a unit of time.

melt-through. Visible root reinforcement in a joint welded from one side. See also **root reinforcement** and **root surface.**

metal. An opaque, lustrous, elemental chemical substance that is a good conductor of heat and electricity, usually malleable, ductile, and more dense than other elemental substances.

metal-bath dip brazing. A dip brazing process variation.

metal cored electrode. A composite tubular filler metal electrode consisting of a metal sheath and a core of various powdered materials, producing no more than slag islands on the face of a weld bead.

metal electrode. A filler or nonfiller metal electrode used in arc welding and cutting that consists of a metal wire or rod that has been manufactured by any method and that is either bare or covered.

metallic bond. The principal bond that holds metals together. It is a primary bond arising from the increased spatial extension of the valence electron wave functions when an aggregate of metal atoms is brought close together. See also **bonding force, covalent bond, ionic bond**, and **mechanical bond**.

metallizing. A nonstandard term when used for **thermal spraying** or the application of a metal coating.

metallurgical bond. A nonstandard term for **metallic bond.**

metal powder cutting (OC-P). An oxygen cutting process that uses heat from an oxyfuel gas flame, with iron or other metal powder to aid cutting.

metal transfer mode, *gas metal arc welding*. The manner in which molten metal travels from the end of a consumable electrode across the welding arc to the workpiece. See also **globular transfer, pulsed spray transfer, rotational spray transfer, short circuiting transfer,** and **spray transfer.**

microetch test. A test in which the specimen is prepared with a polished finish, etched, and examined under high magnification.

microexamination. A metallographic examination in which a prepared surface is examined at high magnification.

MIG welding. A nonstandard term for **flux cored arc welding** or **gas metal arc welding**.

mismatch. See **weld joint mismatch**.

mixed zone. The portion of the weld metal consisting of a mixture of base metal and filler metal. See also **unmixed zone**.

mixing chamber. That part of a welding or cutting torch in which a fuel gas and oxygen are mixed.

molding shoe. A nonstandard term for **backing shoe**.

molten weld pool. A nonstandard term for **weld pool**.

moving shoe. A backing shoe that slides along the joint during welding.

multipass weld. A fusion weld produced by more than one progression of the arc, flame, or energy source along the joint.

multiple-impulse welding. A resistance welding process variation in which welds are made by more than one impulse.

multiport nozzle. A constricting nozzle of the plasma arc torch that contains two or more orifices located in a configuration to achieve some control over the arc shape.

multiple welding position. An orientation for a nonrotated circumferential joint requiring welding in more than one welding position. See **5F**, **5G**, **6F**, **6G**, and **6GR**.

N

narrow gap welding. A nonstandard term for **narrow groove welding.**

narrow groove welding. A variation of a welding process that uses multiple-pass welding with filler metal. The use of a small root opening, with either a square groove or a V-groove and a small groove angle, yields a weld with a high ratio of depth to width.

neutral flame. An oxyfuel gas flame that has neither oxidizing nor reducing characteristics. See also **carburizing flame**, **oxidizing flame**, and **reducing flame**.

neutral flux, *submerged arc welding***.** A flux formulated to produce a weld metal composition that is not dependent on the welding parameters, especially arc voltage. See also **active flux** and **alloy flux.**

nonbutting member. A joint member that is free to move in any direction perpendicular to its thickness dimension. For example, both members of a lap joint, or one member of a T-joint or corner joint. See also **butting member**.

nonconsumable electrode. An electrode that does not provide filler metal.

noncorrosive flux. A soldering flux that in either its original or residual form does not chemically attack the base metal. It usually is composed of rosin-base materials.

nondestructive evaluation. A nonstandard term for **nondestructive examination.**

nondestructive examination (**NDE**)**.** The act of determining the suitability of some material or component for its intended purpose using techniques that do not affect its serviceability.

nondestructive inspection. A nonstandard term when used for **nondestructive examination.**

nondestructive testing. A nonstandard term when used for **nondestructive examination.**

nonsynchronous initiation. The closing of a resistance welding contactor without regard to the voltage wave form position.

nonsynchronous timing. A nonstandard term for **nonsynchronous initiation**.

nontransferred arc. An arc established between the electrode and the constricting nozzle of the plasma arc torch or thermal spraying gun. The workpiece is not in the electrical circuit. See also **transferred arc**.

nonvacuum electron beam welding (EBW-NV). An electron beam welding process variation in which welding is accomplished at atmospheric pressure.

nozzle. See **constricting nozzle**, **gas nozzle**, and **insulating nozzle.**

nozzle, *arc spraying*. A device at the exit end of the gun that directs the atomizing air or other gas.

nozzle, *flame spraying*. A device at the exit end of the gun that directs and forms the flow shape of atomized spray particles and the accompanying air or other gases.

nozzle accumulation. Filler metal or surfacing material deposited on the inner surface and on the exit end of the nozzle.

nugget. The weld metal joining the workpieces in spot, seam, or projection welds.

nugget size. A nonstandard term when used for **resistance spot weld size.**

O

off time, *resistance welding*. The time during which the electrodes are off the workpieces. This term is generally used when the welding cycle is repetitive.

1F, *pipe*. A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in the flat welding position by rotating the pipe about its axis. See Figure A.11(A).

1F, *plate*. A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the flat welding position.

1G, *pipe*. A welding test position designation for a circumferential groove weld applied to a joint in pipe, in which the weld is made in the flat welding position by rotating the pipe about its axis. See Figure A.10(A).

1G, *plate*. A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the flat welding position.

open butt joint. A nonstandard term when used for a **butt joint** with a root opening and with no backing.

open circuit voltage. The voltage between the output terminals of the power source when no current is flowing to the torch or gun.

open groove. A nonstandard term for **open root joint**.

open joint. A nonstandard term for **open root joint**.

open root joint. An unwelded joint without backing or consumable insert.

orifice. See **constricting orifice**.

orifice gas. The gas that is directed into the plasma arc torch or thermal spraying gun to surround the electrode. It becomes ionized in the arc to form the arc plasma and issues from the constricting orifice of the nozzle as a plasma jet.

orifice throat length. The length of the constricting orifice in the plasma arc torch or thermal spraying gun.

oscillation. An alternating motion relative to the direction of travel in a welding, brazing, soldering, thermal cutting, or thermal spraying process device. See also **weaving** and **whipping**.

oven soldering. A nonstandard term for **furnace soldering**.

overhang. A nonstandard term when used for **extension**.

overhead position. See **overhead welding position**.

overhead welding position. The welding position in which welding is performed from the underside of the joint. See Figures A.8, A.9, and A.11(D).

overlap, *fusion welding*. The protrusion of weld metal beyond the weld toe or weld root. See Figures A.15(C) and A.15(D).

overlap, *resistance seam welding*. The portion of the preceding weld nugget remelted by the succeeding weld.

overlap. A nonstandard term when used for **incomplete fusion**.

overlaying. A nonstandard term when used for **surfacing**.

overspray, *thermal spraying*. The portion of the thermal spray deposit that is not deposited on the workpiece.

oxidizing flame. An oxyfuel gas flame in which there is an excess of oxygen, resulting in an oxygen-rich zone extending around and beyond the cone. See also **carburizing flame, neutral flame**, and **reducing flame**.

oxyacetylene cutting (OFC-A). An oxyfuel gas cutting process variation that uses acetylene as the fuel gas.

oxyacetylene welding (OAW). An oxyfuel gas welding process that uses acetylene as the fuel gas. The process is used without the application of pressure.

oxyfuel gas cutter. One who performs oxyfuel gas cutting.

oxyfuel gas cutting (OFC). A group of oxygen cutting processes that uses heat from an oxyfuel gas flame. See also **oxyacetylene cutting, oxyhydrogen cutting, oxynatural gas cutting,** and **oxypropane cutting.**

oxyfuel gas cutting torch. A device used for directing the preheating flame produced by the controlled combustion of fuel gases and to direct and control the cutting oxygen.

oxyfuel gas spraying. A nonstandard term for **flame spraying.**

oxyfuel gas welding (OFW). A group of welding processes that produces coalescence of workpieces by heating them with an oxyfuel gas flame. The processes are used with or without the application of pressure and with or without filler metal.

oxyfuel gas welding torch. A device used in oxyfuel gas welding, torch brazing, and torch soldering for directing the heating flame produced by the controlled combustion of fuel gases.

oxygas cutting. A nonstandard term for **oxyfuel gas cutting.**

oxygen arc cutting (OAC). An oxygen cutting process that uses an arc between the workpiece and a consumable tubular electrode, through which oxygen is directed to the workpiece.

oxygen cutter. See **thermal cutter.**

oxygen cutting (OC). A group of thermal cutting processes that severs or removes metal by means of the chemical reaction between oxygen and the base metal at elevated temperature. The necessary temperature is maintained by the heat from an arc, an oxyfuel gas flame, or other source.

oxygen cutting operator. See **thermal cutting operator.**

oxygen gouging (OG). Thermal gouging that uses an oxygen cutting process variation to form a bevel or groove.

oxygen grooving. A nonstandard term for **oxygen gouging.**

oxygen lance. A length of pipe used to convey oxygen to the point of cutting in oxygen lance cutting.

oxygen lance cutting (OLC). An oxygen cutting process that uses oxygen supplied through a consumable lance. Preheat to start the cutting is obtained by other means.

oxygen lancing. A nonstandard term for **oxygen lance cutting.**

oxyhydrogen cutting (OFC-H). An oxyfuel gas cutting process variation that uses hydrogen as the fuel gas.

oxyhydrogen welding (OHW). An oxyfuel gas welding process that uses hydrogen as the fuel gas. The process is used without the application of pressure.

oxynatural gas cutting (OFC-N). An oxyfuel gas cutting process variation that uses natural gas as the fuel gas.

oxypropane cutting (OFC-P). An oxyfuel gas cutting process variation that uses propane as the fuel gas.

P

parallel gap welding. A nonstandard term when used for **series welding** with closely spaced electrodes.

parallel welding. A resistance welding secondary circuit variation in which the secondary current is divided and conducted through the workpieces and electrodes in parallel electrical paths to form simultaneously multiple resistance spot, seam, or projection welds.

parent metal. A nonstandard term for **base metal** or **substrate.**

partial joint penetration weld. A groove weld in which incomplete joint penetration exists. See Figures A.14(A), A.14(B), A.14(C), A.14(D), A.14(E), A.14(H), A.14(I), and A.14(J). See also **complete joint penetration, complete joint penetration weld, incomplete joint penetration,** and **joint penetration.**

pass. See **thermal spraying pass** and **weld pass.**

pass sequence. See **weld pass sequence.**

paste brazing filler metal. A mixture of finely divided brazing filler metal with a flux or neutral carrier.

paste solder. A mixture of finely divided solder with a flux or neutral carrier.

peel test. A destructive method of testing that mechanically separates a lap joint by peeling.

peening. The mechanical working of metals using impact blows.

penetration. A nonstandard term when used for **depth of fusion**, **joint penetration**, or **root penetration**.

penetration-enhancing flux, *gas tungsten arc welding*. A material applied to the base metal surface adjacent to the weld joint prior to gas tungsten arc welding that results in increased weld penetration.

percent ferrite. A nonstandard term when used for **Ferrite Number.**

percussion welding (PEW). A welding process that produces coalescence with an arc resulting from a rapid discharge of electrical energy. Pressure is applied percussively during or immediately following the electrical discharge.

pilot arc. A low current arc between the electrode and the constricting nozzle of the plasma arc torch to ionize the gas and facilitate the start of the welding arc.

piping porosity. A form of porosity having a length greater than its width that lies approximately perpendicular to the weld face.

plasma. See **arc plasma**.

plasma arc cutting (PAC). An arc cutting process that uses a constricted arc and removes the molten metal with a high-velocity jet of ionized gas issuing from the constricting orifice.

plasma arc cutting torch. A device used to transfer current to a fixed cutting electrode, position the electrode, and direct the flow of shielding gas and orifice gas.

plasma arc welding (PAW). An arc welding process that uses a constricted arc between a nonconsumable electrode and the weld pool (transferred arc) or between the electrode and the constricting nozzle (nontransferred arc). Shielding is obtained from the ionized gas issuing from the torch, which may be supplemented by an auxiliary source of shielding gas. The process is used without the application of pressure. See also **hot wire welding**.

plasma arc welding torch. A device used to transfer current to a fixed welding electrode, position the electrode, and direct the flow of shielding gas and orifice gas.

plasma sprayer. See **thermal sprayer.**

plasma spraying (PSP). A thermal spraying process in which a nontransferred arc is used to create an arc plasma for melting and propelling the surfacing material to the substrate. See also **vacuum plasma spraying.**

plasma spraying operator. See **thermal spraying operator.**

platen, *resistance welding*. A member with a substantially flat surface to which dies, fixtures, backups, or electrode holders are attached and that transmits the electrode force or upset force. One platen is usually fixed and the other moveable.

platen spacing. The distance between adjacent surfaces of the platens in a resistance welding machine.

plenum. See **plenum chamber.**

plenum chamber. The space between the electrode and the inside wall of the constricting nozzle of the plasma arc torch or thermal spraying gun.

plug weld. A weld made in a circular hole in one member of a joint fusing that member to another member. A fillet-welded hole is not to be construed as conforming to this definition.

plug weld size. The diameter of the weld metal in the plane of the faying surfaces.

poke welding. A nonstandard term for **push welding.**

polarity. See **direct current electrode negative** and **direct current electrode positive.**

porosity. Cavity-type discontinuities formed by gas entrapment during solidification or in a thermal spray deposit.

position. See **welding position.**

positional usability. A measure of the relative ease of application of a welding filler metal to make a sound weld in a given welding position and progression.

position of welding. See **welding position.**

postflow time. The time interval from current shut off to either shielding gas or cooling water shut off.

postheating. The application of heat to an assembly after brazing, soldering, thermal spraying, thermal cutting, or welding.

postweld interval, *resistance welding*. The total elapsed time from the end of the weld interval to the end of hold time.

powder alloy. A nonstandard term for **alloy powder.**

powder blend. A mixture of two or more alloy, metal, or nonmetal powders. See also **alloy powder.**

powder composite. Two or more different materials combined to form a single particle, formed by either chemical coating or mechanical agglomeration.

powder cutting. A nonstandard term for **flux cutting** and **metal powder cutting.**

powder feeder. A device for supplying powdered material for thermal cutting, thermal spraying or welding.

powder feed gas. A nonstandard term for **carrier gas.**

powder feed rate. The quantity of powder fed to a thermal spraying gun or a cutting torch per unit of time.

powder flame spraying. A flame spraying process variation in which the surfacing material is in powder form. See also **flame spraying.**

power source. An apparatus for supplying current and voltage suitable for welding, thermal cutting, or thermal spraying.

power supply. A nonstandard term when used for **power source.**

precoating. Coating the base metal in the joint by dipping, electroplating, or other applicable means prior to soldering or brazing.

preflow time. The time interval between start of shielding gas flow and arc starting.

preform. Brazing or soldering filler metal fabricated in a shape or form for a specific application.

preheat. The heat applied to the base metal or substrate to attain and maintain preheat temperature.

preheat current, *resistance welding*. An impulse or series of impulses that occur prior to and are separated from the welding current.

preheat temperature, *brazing* and *soldering*. The temperature of the base metal in the volume surrounding the point of brazing or soldering immediately before brazing or soldering is started.

preheat temperature, *thermal cutting*. The temperature of the base metal in the volume surrounding the point of thermal cutting immediately before thermal cutting is started.

preheat temperature, *thermal spraying*. The temperature of the substrate in the volume surrounding the point of thermal spraying immediately before thermal spraying is started. In a multipass thermal spraying, it is also the temperature immediately before the second and subsequent passes are started.

preheat temperature, *welding*. The temperature of the base metal in the volume surrounding the point of welding immediately before welding is started. In a multipass weld, it is also the temperature immediately before the second and subsequent passes are started.

preheat time, *resistance welding*. The duration of preheat current flow during the preweld interval.

prequalified welding procedure specification (PWPS). A welding procedure specification that complies with the stipulated conditions of a particular welding code or specification and is therefore acceptable for use under that code or specification without a requirement for qualification testing.

pressure-controlled resistance welding (RW-PC). A resistance welding process variation in which a number of spot or projection welds are made with several electrodes functioning progressively under the control of a pressure-sequencing device.

pressure gas welding (PGW). An oxyfuel gas welding process that produces a weld simultaneously over the entire faying surfaces. The process is used with the application of pressure and without filler metal.

pressure welding. A nonstandard term when used for **cold welding, diffusion welding, forge welding, hot pressure welding, pressure gas welding,** and **solid-state welding.**

pretinning. A nonstandard term for **precoating.**

preweld interval, *resistance welding*. The elapsed time between the initiation of the squeeze time and the beginning of the weld time or weld interval time.

procedure. The detailed elements of a process or method used to produce a specific result.

procedure qualification. The demonstration that welds made by a specific procedure can meet prescribed standards.

procedure qualification record (PQR). See **brazing procedure qualification record** and **welding procedure qualification record.**

process. A grouping of basic operational elements used in brazing, soldering, thermal cutting, thermal spraying, or welding. See Figures A.17 and A.18.

progressive block sequence. A block sequence in which successive blocks are completed progressively along the weld, either from one end to the other or from an intermediate location of the weld toward either end. See also **selective block sequence.**

projection welding (PW). A resistance welding process that produces a weld by the heat obtained from the resistance to the flow of the welding current. The resulting welds are localized at predetermined points by projections, embossments, or intersections.

projection weld size. The diameter of the weld metal in the plane of the faying surfaces.

protective atmosphere. A gas or vacuum envelope surrounding the workpieces used to prevent or reduce the formation of oxides and other detrimental surface substances and to facilitate their removal.

puddle. A nonstandard term when used for **weld pool.**

puddle weld. A nonstandard term for an **arc spot weld** or **plug weld.**

pull gun technique. A nonstandard term for **backhand welding.**

pulsation welding. A nonstandard term for **multiple-impulse welding.**

pulse, *resistance welding*. A current of controlled duration of either polarity through the welding circuit.

pulsed gas metal arc welding (GMAW-P). A gas metal arc welding process variation in which the current is pulsed. See also **pulsed power welding.**

pulsed gas tungsten arc welding (GTAW-P). A gas tungsten arc welding process variation in which the current is pulsed. See also **pulsed power welding.**

pulsed laser. A laser whose output is controlled to produce a pulse whose duration is 25 milliseconds or less.

pulsed power welding. An arc welding process variation in which the welding power source is programmed to cycle between low and high power levels.

pulsed spray transfer, *gas metal arc welding*. A variation of spray transfer in which the welding power is cycled from a low level to a high level, at which point spray transfer is attained, resulting in a lower average voltage and current. See also **globular transfer, short circuiting transfer,** and **spray transfer.**

pulsed spray welding. An arc welding process variation in which pulsed spray transfer occurs.

pulse start delay time. The time interval from current initiation to the beginning of current pulsation.

pulse time, *resistance welding*. The duration of a pulse.

purge. The introduction of a gas to remove contaminants from a system or provide backing during welding.

push angle. The travel angle when the electrode is pointing in the direction of weld progression. This angle can also be used to partially define the position of guns, torches, rods, and beams. See also **drag angle, forehand welding, travel angle,** and **work angle.**

push welding. A resistance welding process variation in which spot or projection welds are made by manually applying force to one electrode and using the workpiece or a support as the other electrode.

Q

qualification. See procedure qualification and welder performance qualification.

quench time, *resistance welding*. The time from the end of the weld, weld interval, or downslope time to the beginning of the temper time, during which no current flows through the workpieces and the weld is rapidly cooled by the electrodes.

R

random intermittent welds. Intermittent welds on one or both sides of a joint in which the weld increments are made without regard to spacing.

random sequence. A longitudinal sequence in which the weld bead increments are made at random.

random wound. Spooled or coiled filler metal that has not been wound in distinct layers. See also **level wound.**

rate of deposition. See **deposition rate.**

rate of flame propagation. See **flame propagation rate.**

reaction flux, *soldering*. A flux composition in which one or more of the ingredients reacts with a base metal upon heating to deposit one or more metals.

reaction soldering. A soldering process variation in which a reaction flux is used.

reaction stress. A stress that cannot exist in a member if the member is isolated as a free body without connection to other parts of the structure.

reactor. A device used in arc welding circuits to minimize irregularities in the flow of the welding current.

reconditioned flux, *submerged arc welding*. Virgin or recycled flux that has been processed for use or reuse. The processing may include screening for particle sizing, removal of magnetic particles and baking to remove moisture.

recrushed slag. A nonstandard term when used for **recycled slag.**

recycled flux, *submerged arc welding*. Unfused granular flux remaining after welding that has been recovered for reuse. See also **virgin flux**.

recycled slag, *submerged arc welding*. Fused slag remaining after welding that has been recovered and processed for reuse.

reduced section tension test. A test in which a transverse section of the weld is located in the center of the reduced section of the specimen.

reducing atmosphere. A chemically active protective atmosphere that will reduce metal oxides to their metallic state at elevated temperature.

reducing flame. An oxyfuel gas flame with an excess of fuel gas. See also **carburizing flame, neutral flame, oxidizing flame**, and **reducing atmosphere**.

reflowing. A nonstandard term when used for **flow brightening**.

reflow soldering. A nonstandard term for **soldering** with preplaced filler metal.

residual stress. Stress present in a joint member or material that is free of external forces or thermal gradients.

resistance brazing (RB). A brazing process that uses heat from the resistance to electric current flow in a circuit of which the workpieces are a part.

resistance butt welding. A nonstandard term for **flash welding** and **upset welding.**

resistance seam welding (RSEW). A resistance welding process that produces a weld at the faying surfaces of overlapped parts progressively along a length of a joint. The weld may be made with overlapping weld nuggets, a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by resistance to the flow of the welding current. See Figure A.7(D) See also **high-frequency seam welding** and **induction seam welding.**

resistance seam weld size. See **seam weld size.**

resistance soldering (RS). A soldering process that uses heat from the resistance to electric current flow in a circuit of which the workpieces are a part.

resistance spot welding (RSW). A resistance welding process that produces a weld at the faying surfaces of a joint by the heat obtained from resistance to the flow of welding current through the workpieces from electrodes that serve to concentrate the welding current and pressure at the weld area. See Figures A.7(E) and A.7(F).

resistance spot weld size. See **spot weld size.**

resistance welding (RW). A group of welding processes that produces coalescence of the faying surfaces with the heat obtained from resistance of the workpieces to the flow of the welding current in a circuit of which the workpieces are a part and by the application of pressure. See Figure A.17.

resistance welding control. The device, usually electronic, that determines the welding sequence and timing with regard to the welding current pattern, electrode or platen force or movement, and other operational conditions of a resistance welding machine.

resistance welding current. The current in the welding circuit during the making of a weld, but excluding preweld or postweld current.

resistance welding die. A resistance welding electrode usually shaped to the workpiece contour to clamp the workpieces and to conduct the welding current.

resistance welding downslope time. The time during which the welding current is continuously decreased.

resistance welding electrode. The part of a resistance welding machine through which the welding current and, in most cases, force are applied directly to the workpiece. The electrode may be in the form of a rotating wheel, rotating roll, bar, cylinder, plate, clamp, chuck, or modification thereof.

resistance welding gun. A manipulatable device to transfer current and provide electrode force to the weld area (usually in reference to a portable gun).

resistance welding upslope time. The time during which the welding current continuously increases from the beginning of the welding current.

resistance welding voltage. The voltage through the workpieces, between the resistance welding electrodes.

resistance welding weld time. The duration of welding current flow through the workpieces in making a weld by single-impulse welding or flash welding. See also **weld interval.**

retaining shoe. A nonstandard term for **backing shoe.**

reverse polarity. A nonstandard term for **direct current electrode positive.**

robotic, *adj*. Pertaining to process control by robotic equipment. See also **adaptive control, automatic, manual, mechanized,** and **semiautomatic.**

robotic brazing. See **robotic welding.**

robotic soldering. See **robotic welding.**

robotic thermal cutting. See **robotic welding.**

robotic thermal spraying. See **robotic welding.**

robotic welding. Welding that is performed and controlled by robotic equipment. Variations of this term are **robotic brazing, robotic soldering, robotic thermal cutting,** and **robotic thermal spraying.** See also **adaptive control welding, automatic welding, manual welding, mechanized welding,** and **semiautomatic welding.**

rollover. A nonstandard term when used for **overlap,** *fusion welding***.**

roll spot welding. A resistance welding process variation that makes intermittent spot welds using one or more rotating circular electrodes. The rotation of the electrodes may or may not be stopped during the making of a weld.

roll welding (ROW). A solid-state welding process that produces a weld by the application of heat and sufficient pressure with rolls to cause deformation at the faying surfaces. See also **forge welding.**

root. A nonstandard term when used for **joint root** or **weld root.**

root bead. A weld bead that extends into or includes part or all of the joint root.

root bend test. A test in which the weld root is on the convex surface of a specified bend radius.

root crack. See Figure A.16.

root edge. A root face of zero width. See Figure A.3.

root face. That portion of the groove face within the joint root. See Figure A.3.

root face extension. An extension of the base metal adjacent to the root face in a bevel or J edge shape beyond the bevel or bevel radius, respectively, to provide for improved weld penetration control or joint root access.

root gap. A nonstandard term for **root opening.**

root of joint. See **joint root.**

root of weld. See **weld root.**

root opening. A separation at the joint root between the workpieces. See Figures A.4(A) and A.4(E).

root pass. A weld pass made to produce a root bead.

root penetration. The distance the weld metal extends into the joint root. See Figure A.14.

root radius. A nonstandard term for **bevel radius.**

root reinforcement. Weld reinforcement opposite the side from which welding was done. See Figure A.13(A). See also **face reinforcement.**

root surface. The exposed surface of a weld opposite the side from which welding was done. See Figure A.13(B).

root surface crack. A crack in the exposed surface of a weld. See Figure A.16.

root surface underfill. See **underfill**. See Figure A.15(E).

rotary roughening, *thermal spraying*. A method of surface roughening in which a revolving tool is pressed against the surface being prepared, while either the work or the tool, or both, move. See also **groove and rotary roughening**, **knurling**, and **threading and knurling**.

rotational spray transfer, *gas metal arc welding*. A variation of spray transfer in which a longer electrode extension and specialized gas mixtures are used to produce a helical pattern of very fine droplets.

rough threading, *thermal spraying*. A method of surface roughening that consists of cutting threads with the sides and tops of the threads jagged and torn.

round edge shape. A type of edge shape in which the surface is curved.

runoff weld tab. Additional material that extends beyond the end of the joint, on which the weld is terminated. See also **starting weld tab**.

S

salt-bath dip brazing. A dip brazing process variation.

scarf. A nonstandard term for **bevel**.

scarf groove. A weld groove formed by the combination of butting members having single-bevel edge shapes arranged with parallel groove faces.

scarf joint. A nonstandard term for **scarf groove**.

seal-bonding material, *thermal spraying*. A material that partially forms, in the as-sprayed condition, a metallic bond with the substrate.

seal coat, *thermal spraying*. Material applied to infiltrate and close the pores of a thermal spray deposit.

seal weld. Any weld intended primarily to provide a specific degree of tightness against leakage.

seam. A nonstandard term when used for a brazed, soldered or welded, joint.

seam weld. A continuous weld made between or upon overlapping members, in which coalescence may start and occur on the faying surfaces, or may have proceeded from the outer surface of one member. The continuous weld may consist of a single weld bead or a series of overlapping spot welds. See Figure A.7. See also **arc seam weld** and **resistance seam welding**.

seam weld size. The width of the weld metal in the plane of the faying surfaces.

secondary circuit. That portion of a welding machine that conducts the secondary current between the secondary terminals of the welding transformer and the electrodes, or electrode and workpiece.

secondary current path, *resistance welding*. The electrical path through which the welding current passes.

selective block sequence. A block sequence in which successive blocks are completed in an order selected to control residual stresses and distortion. See also **progressive block sequence**.

self-fluxing alloy, *thermal spraying*. A surfacing material that wets the substrate and coalesces when heated to its melting point, with no flux other than the boron and silicon contained in the alloy.

self-shielded flux cored arc welding (FCAW-S). A flux cored arc welding process variation in which shielding gas is obtained exclusively from the flux within the electrode.

semiautomatic, *adj*. Pertaining to the manual control of a process with equipment that automatically controls one or more of the process conditions. See also **adaptive control, automatic, manual, mechanized,** and **robotic**.

semiautomatic brazing. See **semiautomatic welding**.

semiautomatic soldering. See **semiautomatic welding.**

semiautomatic thermal cutting. See **semiautomatic welding.**

semiautomatic thermal spraying. See **semiautomatic welding.**

semiautomatic welding. Manual welding with equipment that automatically controls one or more of the welding conditions. Variations of this term are **semiautomatic brazing, semiautomatic soldering, semiautomatic thermal cutting**, and **semiautomatic thermal spraying**. See also **adaptive control welding, automatic welding, manual welding, mechanized welding**, and **robotic welding**.

semiblind joint. A joint in which one extremity of the joint is not visible.

sequence time. A nonstandard term when used for **welding cycle**.

series submerged arc welding (**SAW-S**). A submerged arc welding process variation in which the arc is established between two consumable electrodes that meet just above the surface of the workpieces, which are not part of the welding current circuit.

series welding. A resistance welding secondary circuit variation in which the secondary current is conducted through the workpieces and electrodes or wheels in a series electrical path to simultaneously form multiple resistance spot, seam, or projection welds.

setback. See **contact tip setback** and **electrode setback**.

set down. A nonstandard term when used for **upset**.

shadow mask, *thermal spraying*. A device that partially shields an area of the workpiece, producing a feathered edge of the thermal spray deposit.

sheet separation, *resistance welding*. The distance between the faying surfaces, adjacent to the weld, after a spot, seam, or projection weld has been made.

shielded carbon arc welding (**CAW-S**). A carbon arc welding process variation that uses shielding from the combustion of solid material fed into the arc, or from a blanket of flux on the workpieces, or both.

shielded metal arc cutting (**SMAC**). An arc cutting process that uses a covered electrode.

shielded metal arc welding (**SMAW**). An arc welding process with an arc between a covered electrode and the weld pool. The process is used with shielding from the decomposition of the electrode covering, without the application of pressure, and with filler metal from the electrode. See also **firecracker welding.**

shielding gas. Protective gas used to prevent or reduce atmospheric contamination. See also **protective atmosphere.**

short arc. A nonstandard term when used for **short circuiting transfer.**

short circuit gas metal arc welding (**GMAW-S**). A gas metal arc welding process variation in which the consumable electrode is deposited during repeated short circuits.

short circuiting arc welding. A nonstandard term for **short circuit gas metal arc welding.**

short circuiting transfer, *gas metal arc welding*. Metal transfer in which molten metal from a consumable electrode is deposited during repeated short circuits. See also **globular transfer** and **spray transfer.**

shoulder. A nonstandard term when used for **root face.**

shrinkage stress. A nonstandard term when used for **residual stress.**

shrinkage void. A cavity-type discontinuity normally formed by shrinkage during solidification.

sidewall. A nonstandard term when used for **bevel face** or **groove face.**

sieve analysis. A method of determining particle size distribution, usually expressed as the weight percentage retained upon each of a series of standard screens of decreasing mesh size.

side bend test. A test in which the side of a transverse section of the weld is on the convex surface of a specified bend radius.

silver alloy brazing. A nonstandard term when used for **brazing** with a silver-base filler metal.

silver soldering. A nonstandard term for **brazing** with a silver-base filler metal.

single-bevel edge shape. A type of bevel edge shape having one prepared surface.

single-bevel groove. A weld groove formed by the combination of a butting member having a bevel edge shape and a planar surface of a companion member or a butting member with a square edge shape and a skewed surface of a nonbutting member. See Figure A.5(B).

single-bevel-groove weld. A weld in a single-bevel groove welded from one side. See Figure A.5(B).

single-flare-bevel groove. A weld groove formed by the combination of a butting member having a round edge shape and a planar surface of a companion member. See Figure A.5(H).

single-flare-bevel-groove weld. A weld in a single-flare-bevel groove welded from one side. See Figure A.5(H).

single-flare-V groove. A weld groove formed by the combination of butting members having round edge shapes. See Figure A.5(I).

single-flare-V-groove weld. A weld in a single-flare-V groove welded from one side. See Figure A.5(I).

single-groove weld, *fusion welding*. A groove weld that is made from one side only. See Figure A.5.

single impulse welding. A resistance welding process variation in which spot, projection, or upset welds are made with a single pulse.

single-J edge shape. A type of J-edge shape having one prepared surface.

single-J groove. A weld groove formed by the combination of a butting member having a single-J edge shape abutting a planar surface of a companion member. See Figure A.5(F).

single-J-groove weld. A weld in a single-J-groove welded from one side. See Figure A.5(F).

single-port nozzle. A constricting nozzle of the plasma arc torch that contains one orifice, located below and concentric with the electrode.

single-spliced butt joint. See **spliced joint.**

single-spliced joint. See **spliced joint.**

single-square-groove weld. A weld in a square groove welded from one side. See Figure A.5(A).

single-U groove. A weld groove formed by the combination of two butting members having single-J edge shapes. See Figure A.5(G).

single-U-groove weld. A weld in a single-U groove welded from one side. See Figure A.5(G).

single-V groove. A V-shaped weld groove formed by the combination of (a) butting members having single-bevel edge shapes, (b) butting and nonbutting members having planar surfaces arranged to form a groove, or (c) a V-shaped groove in the surface of a member. See Figures A.5(C), A.5(D), and A.5(E).

single-V-groove weld. A weld in a single-V groove welded from one side. See Figures A.5(C), A.5(D), and A.5(E).

single-welded joint, *fusion welding*. A joint that is welded from one side only. See Figure A.5.

6F. A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in flat, vertical, and overhead welding positions. The pipe remains fixed until welding is complete. See Figure A.11(F).

6G. A welding test position designation for a circumferential groove weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in the flat, vertical, and overhead welding positions. The pipe remains fixed until welding is complete. See Figure A.10(D).

6GR. A welding test position designation for a circumferential groove weld applied to a joint in pipe, with its axis approximately 45° from horizontal, in which the weld is made in the flat, vertical, and overhead welding positions. A restriction ring is added, adjacent to the joint, to restrict access to the weld. The pipe remains fixed until welding is complete. See Figure A.10(E).

size of weld. See **weld size.**

skip weld. A nonstandard term for **intermittent weld.**

skull. The unmelted residue from a liquated filler metal.

slag. A nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in some welding and brazing processes.

slag inclusion. A discontinuity consisting of slag entrapped in weld metal or at the weld interface.

slot weld. A weld made in an elongated hole in one member of a joint fusing that member to another member. The hole may be open at one end. A fillet-welded slot is not to be construed as conforming to this definition.

slot weld size. The width and length of the weld metal in the plane of the faying surfaces.

slugging. The unauthorized addition of metal, such as a length of rod, to a joint before welding or between passes, often resulting in a weld with incomplete fusion.

smoothing bead. A weld bead made to correct an undesirable weld surface contour. See also **cosmetic weld bead.**

smoothing pass. A weld pass that results in a smoothing bead. See also **cosmetic weld pass.**

soft solder. A nonstandard term for **solder.**

solder. The metal or alloy used as a filler metal in soldering, which has a liquidus not exceeding 450°C (840°F) and below the solidus of the base metal.

solder, *v.* The act of soldering.

solderability. The capacity of a material to be soldered under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service.

soldering (S). A group of joining processes that produces coalescence of materials by heating them to the soldering temperature and by using a filler metal having a liquidus not exceeding 450°C (840°F) and below the solidus of the base metals. The filler metal is distributed between closely fitted faying surfaces of the joint by capillary action or by wetting the surfaces of the workpieces. See Figures A.17, A.19, and A.22.

soldering blowpipe. A device used to obtain a small, accurately directed flame for fine work. A portion of any flame is blown to the desired location by the blowpipe, which is usually mouth operated.

soldering gun. An electrical soldering iron with a pistol grip and a quick heating, relatively small bit.

soldering iron. A soldering tool having an internally or externally heated metal bit usually made of copper.

solder interface. The interface between solder metal and base metal in a soldered joint.

solder metal. That portion of a soldered joint that has been melted during soldering.

solid state welding (SSW). A group of welding processes that produce coalescence by the application of pressure without melting any of the joint components. See Figures A.17, A.19, and A.21.

solidus. The highest temperature at which a metal or an alloy is completely solid.

spacer. See **joint spacer.**

spacer strip. A nonstandard term when used for **joint spacer.**

spatter. The metal particles expelled during fusion welding that do not form a part of the weld.

spatter loss. Metal lost due to spatter.

spiking, *electron beam welding* and *laser beam welding*. A condition where the joint penetration is nonuniform and changes abruptly over the length of the weld.

spit. A nonstandard term when used for **expulsion** and **flash.**

splice. A nonstandard term when used for a brazed, soldered or welded joint.

spliced butt joint. See **spliced joint.**

spliced joint. A joint in which an additional workpiece spans the joint and is welded to each joint member. See also **splice member.**

splice member. The workpiece that spans the joint in a spliced joint.

split layer technique. A welding technique that results in layers having more than one weld bead. See Figure A.12(D).

split pipe backing. A pipe segment used as a backing for welding butt joints in round bars.

spool. A filler metal package consisting of a continuous length of welding wire in coil form wound on a cylinder (called a *barrel*), which is flanged at both ends. The flange contains a spindle hole of smaller diameter than the inside diameter of the barrel.

spot weld. A weld made between or upon overlapping members in which coalescence may start and occur on the faying surfaces or may proceed from the outer surface of one member. The weld cross section (plan view) is approximately circular. See Figures A.7(E), A.7(F), A.7(G), and A.7(H). See also **arc spot weld** and **resistance spot welding.**

spot weld size. The diameter of the weld metal in the plane of the faying surfaces.

spray arc. A nonstandard term for **spray transfer.**

spray deposit. See **thermal spray deposit.**

spray deposit density ratio. See **thermal spray deposit density ratio.**

sprayer. See **thermal sprayer.**

spray-fuse. A thermal spraying technique in which the deposit is reheated to fuse the particles and form a metallurgical bond with the substrate.

spraying booth. An exhaust booth where thermal spraying is performed.

spraying operator. See **thermal spraying operator.**

spraying rate, *thermal spraying*. The rate at which surfacing material passes through the gun.

spraying sequence, *thermal spraying*. The order in which layers of materials are applied, such as overlapped, superimposed, or at various angles.

spray tab, *thermal spraying*. A small piece of additional material that is thermally sprayed concurrently with the workpiece, and used to evaluate the quality of the thermal spray deposit.

spray transfer, *gas metal arc welding*. Metal transfer in which molten metal from a consumable electrode is propelled axially across the arc in small droplets. See also **globular transfer** and **short circuiting transfer.**

square edge shape. A type of edge shape in which the prepared surface lies perpendicular to the material surface.

square groove. A weld groove formed by the combination of a butting member having a square edge shape and a planar surface of a companion member. See Figures A.5(A) and A.6(A).

square-groove weld. A weld in a square groove. See Figures A.5(A) and A.6(A).

squeeze time, *resistance welding*. The time between the initiation of the welding cycle and first application of current in spot, seam, or projection and some types of upset welds.

stack cutting. Thermal cutting of stacked metal plates arranged so that all the plates are severed by a single cut.

staggered intermittent weld. An intermittent weld on both sides of a joint in which the weld increments on one side are alternated with respect to those on the other side. See Figure A.12(H).

standard welding procedure specification (SWPS). A welding procedure specification qualified according to the requirements of ANSI/AWS B2.1,[5] approved by the American Welding Society and made available for production welding by companies or individuals other than those performing the qualification test.

standoff distance. The distance between a nozzle and the workpiece.

start current. The current value during start time interval.

starting weld tab. Additional material that extends beyond the beginning of the joint, on which the weld is started. See also **runoff weld tab.**

start time. The time interval prior to weld time during which arc voltage and current reach a preset value greater or less than welding values.

static electrode force. The force exerted by electrodes on the workpieces in making spot, seam, or projection welds by resistance welding under welding conditions, but with no current flowing and no movement in the welding machine. See also **dynamic electrode force** and **theoretical electrode force.**

stationary shoe. A backing shoe that remains in a fixed position during welding.

stepback sequence. A nonstandard term for **backstep sequence.**

step brazing. The brazing of successive joints on a given part with filler metals of successively lower brazing temperatures so as to accomplish the joining without disturbing the joints previously brazed.

step soldering. The soldering of successive joints on a given part with solders of successively lower soldering temperature so as to accomplish the joining without disturbing the joints previously soldered.

stick electrode. A nonstandard term for **covered electrode.**

stick electrode welding. A nonstandard term for **shielded metal arc welding.**

5. American Welding Society (AWS) Committee on Welding Qualification, *Standard for Welding Procedure and Performance Qualification,* ANSI/AWS B2.1, Miami: American Welding Society.

stickout, *gas metal arc welding* and *gas-shielded flux cored arc welding*. The length of unmelted electrode extending beyond the end of the gas nozzle. See also **electrode extension**.

stickout, *gas tungsten arc welding*. The length of tungsten electrode extending beyond the end of the gas nozzle. See also **electrode extension**.

stitch weld. A nonstandard term for **intermittent weld**.

stop-off. A material used on the surfaces adjacent to the joint to limit the spread of soldering or brazing filler metal.

stored energy welding. A resistance welding process variation in which welds are made with electrical energy accumulated electrostatically, electromagnetically, or electrochemically at a relatively low rate and made available at the required welding rate.

straight polarity. A nonstandard term for **direct current electrode negative**.

stranded electrode. A composite filler metal electrode consisting of stranded wires that may mechanically enclose materials to improve properties, stabilize the arc, or provide shielding.

stress-corrosion cracking. Failure of metals by cracking under combined action of corrosion and stress, residual or applied. In brazing, the term applies to the cracking of stressed base metal due to the presence of a liquid filler metal.

stress-relief cracking. Intergranular cracking in the heat-affected zone or weld metal as a result of the combined action of residual stresses and postweld exposure to an elevated temperature.

stress-relief heat treatment. Uniform heating of a structure or a portion thereof to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling.

strike. See **arc strike**.

stringer bead. A weld bead formed without appreciable weaving. See also **weave bead**.

strongback. A device attached to the members of a weld joint to maintain their alignment during welding.

stub. The short length of filler metal electrode, welding rod, or brazing rod that remains after its use for welding or brazing.

stud arc welding. A nonstandard term for **arc stud welding**.

stud welding. A general term for joining a metal stud or similar part to a workpiece. Welding may be accomplished by arc, resistance, friction, or other process with or without external gas shielding. See also **arc stud welding**.

submerged arc welding (SAW). An arc welding process that uses an arc or arcs between a bare metal electrode or electrodes and the weld pool. The arc and molten metal are shielded by a blanket of granular flux on the workpieces. The process is used without pressure and with filler metal from the electrode and sometimes from a supplemental source (welding rod, flux, or metal granules). See also **hot wire welding** and **series submerged arc welding**.

substrate. Any material to which a thermal spray deposit is applied.

suck-back. A nonstandard term when used for **underfill** at the root surface.

surface expulsion, *resistance welding*. Expulsion occurring at an electrode to workpiece contact rather than at the faying surface. See also **expulsion**.

surface preparation. The operations necessary to produce a desired or specified surface condition.

surface roughening, *thermal spraying*. A group of methods for producing irregularities on a surface. See also **dovetailing**, **groove and rotary roughening**, **rotary roughening**, **rough threading**, and **threading and knurling**.

surfacing. The application by welding, brazing, or thermal spraying of a layer, or layers, of material to a surface to obtain desired properties or dimensions, as opposed to making a joint. See also **buildup**, **buttering**, **cladding**, and **hardfacing**.

surfacing material. The material that is applied to a base metal or substrate during surfacing.

surfacing metal. The metal or alloy that is applied to a base metal or substrate during surfacing.

surfacing weld. A weld applied to a surface, as opposed to making a joint, to obtain desired properties or dimensions.

sweat soldering. A soldering process variation in which workpieces that have been precoated with solder are reheated and assembled into a joint without the use of additional solder.

synchronous timing, *resistance welding*. The initiation of each half cycle of welding transformer primary current on an accurately timed delay with respect to the polarity reversal of the power supply.

T

tab. See **runoff weld tab**, **starting weld tab**, and **weld tab**.

tacker. A nonstandard term for **tack welder.**

tack weld. A weld made to hold the parts of a weldment in proper alignment until the final welds are made.

tack welder. One who performs manual or semiautomatic welding to produce tack welds.

taper delay time. The time interval after upslope during which the maximum welding current or high pulse current is constant.

taper time. The time interval when current increases or decreases continuously from the welding current to final taper current.

tap. A nonstandard term when used for **transformer tap.**

temper time, *resistance welding*. The time following quench time during which a current is passed through the weld for heat treating.

temporary weld. A weld made to attach a piece or pieces to a weldment for temporary use in handling, shipping, or working on the weldment.

tension test. A test in which a specimen is loaded in tension until failure occurs. See also **reduced section test specimen.**

test coupon. A weld, braze or solder assembly for procedure or performance qualification testing.

test specimen. A sample of a test coupon subjected to testing.

theoretical electrode force. The force, neglecting friction and inertia, in making spot, seam, or projection welds, available at the electrodes of a resistance welding machine by virtue of the initial force and the theoretical mechanical advantage of the system. See also **dynamic electrode force** and **static electrode force.**

theoretical throat. The distance from the beginning of the joint root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross section of a fillet weld. This dimension is based on the assumption that the root opening is equal to zero. See also **actual throat** and **effective throat.**

thermal cutter. One who performs manual or semiautomatic thermal cutting. Variations of this term are **arc cutter** and **oxygen cutter.**

thermal cutting (TC). A group of cutting processes that severs or removes metal by localized melting, burning, or vaporizing of the workpieces. See also arc **cutting, high energy beam cutting**, and **oxygen cutting.**

thermal cutting operator. One who operates automatic, mechanized, or robotic thermal cutting equipment. Variations of this term are **arc cutting operator, electron beam cutting operator, laser beam cutting operator**, and **oxygen cutting operator.**

thermal gouging. A thermal cutting process variation that removes metal by melting or burning the entire removed portion, to form a bevel or groove. See also **arc gouging, backgouging**, and **oxygen gouging**.

thermal spray deposit. The coating or layer of surfacing material applied by a thermal spraying process. thermal spray deposit density ratio. The ratio of the density of the thermal spray deposit to the theoretical density of the surfacing material, usually expressed as percent of theoretical density.

thermal spray deposit interface. The interface between the thermal spray deposit and the substrate.

thermal spray deposit strength. The tensile strength of a thermal spray deposit.

thermal spray deposit stress. The residual stress in a thermal spray deposit resulting from rapid cooling of molten or semimolten particles as they impinge on the substrate.

thermal sprayer. One who performs semiautomatic thermal spraying. Variations of this term are **arc sprayer, flame sprayer**, and **plasma sprayer.**

thermal spraying (THSP). A group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a substrate to form a thermal spray deposit. The surfacing material may be in the form of powder, rod, cord, or wire. See also **arc spraying, flame spraying**, and **plasma spraying.**

thermal spraying deposition efficiency. The ratio of the weight of thermal spray deposit to the weight of surfacing material sprayed, expressed in percent.

thermal spraying gun. A device for heating, feeding, and directing the flow of surfacing material.

thermal spraying operator. One who operates automatic, mechanized, or robotic thermal spraying equipment. Variations of this term are **arc spraying operator, flame spraying operator**, and **plasma spraying operator**.

thermal spray pass. A single progression of the thermal spraying gun across the substrate surface.

thermal stress. Stress resulting from nonuniform temperature distribution.

thermite crucible. The vessel in which the thermite reaction takes place.

thermite mixture. A mixture of metal oxide and finely divided aluminum with the addition of alloying metals as required.

thermite mold. A mold formed around the workpieces to receive molten metal.

thermite reaction. The chemical reaction between metal oxide and aluminum that produces superheated molten metal and a slag containing aluminum oxide.

thermite welding (TW). A welding process that produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal is obtained from the liquid metal.

thermocompression bonding. A nonstandard term for **hot pressure welding.**

threading and knurling, *thermal spraying*. A method of surface roughening in which spiral threads are prepared, followed by upsetting with a knurling tool. See also **groove and rotary roughening, knurling,** and **rotary roughening.**

3F. A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the vertical welding position.

3G. A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the vertical welding position.

throat area. The area bounded by the physical parts of the secondary circuit in a resistance spot, seam, or projection welding machine. Used to determine the dimensions of a part that can be welded and determine, in part, the secondary impedance of the equipment.

throat crack. A crack in the throat of a fillet weld. See Figure A.16.

throat depth. In a resistance spot, seam, or projection welding machine, the distance from the centerline of the electrodes or platens to the nearest point of interference for flat sheets.

throat height. The unobstructed dimension between the arms and throughout the throat depth in a resistance welding machine.

throat length. A nonstandard term when used for **constricting orifice length.**

throat of a groove weld. A nonstandard term for **groove weld size.**

throat opening. A nonstandard term for **throat height.**

tie-in, *fusion welding*. The junction of weld metal and base metal or prior weld metal where fusion is intended.

tie-in, *v., fusion welding*. To manipulate the welding process at the junction of the weld metal and base metal or weld metal to facilitate fusion.

TIG welding. A nonstandard term for **gas tungsten arc welding.**

tinning. A nonstandard term when used for **precoating.**

tip. See **cutting tip** and **welding tip.**

tip skid. A nonstandard term for **electrode skid.**

T-joint. A joint between two members located approximately at right angles to each other in the form of a T. See Figure A.1(C).

toe crack. See Figures A.15(A) and A.16.

toe of weld. See **weld toe.**

torch. See **air carbon arc cutting torch, gas tungsten arc cutting torch, gas tungsten arc welding torch, heating torch, oxyfuel gas cutting torch, oxyfuel gas welding torch, plasma arc cutting torch,** and **plasma arc welding torch.**

torch brazing (TB). A brazing process that uses heat from a fuel gas flame.

torch soldering (TS). A soldering process that uses heat from a fuel gas flame.

torch tip. See **cutting tip** and **welding tip**.

transferred arc. A plasma arc established between the electrode of the plasma arc torch and the workpiece. See also **nontransferred arc**.

transformer tap. Connections to a transformer winding that are used to vary the transformer turns ratio, thereby controlling welding voltage and current.

transverse bend specimen. See **transverse weld test specimen**.

transverse crack. A crack with its major axis oriented approximately perpendicular to the weld axis. See Figure A.16.

transverse tension specimen. See **transverse weld test specimen**.

transverse weld test specimen. A weld test specimen with its major axis perpendicular to the weld axis. See also **longitudinal weld test specimen**.

travel angle. The angle less than 90° between the electrode axis and a line perpendicular to the weld axis, in a plane determined by the electrode axis and the weld axis. This angle can also be used to partially define the position of guns, torches, rods, and beams. See also **drag angle**, **push angle**, and **work angle**.

travel angle, *pipe*. The angle less than 90° between the electrode axis and a line perpendicular to the weld axis at its point of intersection with the extension of the electrode axis, in a plane determined by the electrode axis and a line tangent to the pipe surface at the same point. This angle can also be used to partially define the position of guns, torches, rods, and beams. See also **drag angle**, **push angle**, and **work angle**.

travel start delay time. The time interval from arc initiation to the start of the torch, gun, or workpiece travel.

travel stop delay time. The time interval from beginning of downslope time or crater fill time to shut-off of torch, gun, or workpiece travel.

tubular joint. A joint between two or more members, at least one of which is tubular.

tungsten electrode. A nonfiller metal electrode used in arc welding, arc cutting, and plasma spraying, made principally of tungsten.

tungsten inclusion. A discontinuity consisting of tungsten entrapped in weld metal.

twin carbon arc brazing (TCAB). A brazing process that uses heat from an arc between two carbon electrodes. This is an obsolete or seldom used process.

twin carbon arc welding (CAW-T). A carbon arc welding process variation that uses an arc between two carbon electrodes and no shielding.

2F, *pipe*. A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately vertical, in which the weld is made in the horizontal welding position. See Figure A.11(B).

2F, *plate*. A welding test position designation for a linear fillet weld applied to a joint in which the weld is made in the horizontal welding position.

2FR. A welding test position designation for a circumferential fillet weld applied to a joint in pipe, with its axis approximately horizontal, in which the weld is made in the horizontal welding position by rotating the pipe about its axis. See Figure A.11(C).

2G, *pipe*. A welding test position designation for a circumferential groove weld applied to a joint in a pipe, with its axis approximately vertical, in which the weld is made in the horizontal welding position. See Figure A.10(B).

2G, *plate*. A welding test position designation for a linear groove weld applied to a joint in which the weld is made in the horizontal welding position.

type of joint. See joint type.

U

U-groove weld. A type of groove weld. See Figures A.5(G) and A.6(E).

ultrasonic coupler, *ultrasonic soldering* and *ultrasonic welding*. Elements through which ultrasonic vibration is transmitted from the transducer to the tip.

ultrasonic soldering (USS). A soldering process variation in which high-frequency vibratory energy is transmitted through molten solder to remove undesirable surface films and thereby promote wetting of the base metal. This operation is usually accomplished without flux.

ultrasonic welding (USW). A solid-state welding process that produces a weld by the local application of high-frequency vibratory energy as the workpieces are held together under pressure.

ultra-speed welding. A nonstandard term for **commutator-controlled welding.**

underbead crack. A heat-affected zone crack in steel weldments arising from the occurrence of a crack-susceptible microstructure, residual or applied stress, and the presence of hydrogen. See Figures A.15(B) and A.16.

undercut. A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal. See Figures A.15(C) and A.15(D).

underfill. A groove weld condition in which the weld face or root surface is below the adjacent surface of the base metal. See Figures A.15(E) and A.15(F).

unfused flux, *submerged arc welding*. Flux that has not been melted during welding.

unmixed zone. A thin boundary layer of weld metal, adjacent to the weld interface, that solidified without mixing with the remaining weld metal. See also **mixed zone**.

uphill, *adv.* Welding with an upward progression.

upset. Bulk deformation resulting from the application of pressure in welding. The upset may be measured as a percent increase in interface area, a reduction in length, a percent reduction in lap joint thickness, or a reduction in cross wire weld stack height.

upset butt welding. A nonstandard term for **upset welding**.

upset distance. The total reduction in the axial length of the workpieces from the initial contact to the completion of the weld. In flash welding the upset distance is equal to the platen movement from the end of flash time to the end of upset.

upset force. The force exerted at the faying surfaces during upsetting.

upset time. The time during upsetting.

upset welding (UW). A resistance welding process that produces coalescence over the entire area of faying surfaces or progressively along a butt joint by the heat obtained from the resistance to the flow of welding current through the area where those surfaces are in contact. Pressure is used to complete the weld. See also **high-frequency upset welding** and **induction upset welding.**

upslope time. See **automatic arc welding upslope time** and **resistance welding upslope time.**

usability. A measure of the relative ease of application of a welding filler metal to make a sound weld.

V

vacuum brazing. A nonstandard term for various brazing processes that take place in a chamber or retort below atmospheric pressure.

vacuum plasma spraying (VPSP). A thermal spraying process variation using a plasma spraying gun confined to a stable enclosure that is partially evacuated.

vertical-down. A nonstandard term for **downhill.**

vertical position. See **vertical welding position.**

vertical position, *pipe welding*. A nonstandard term when used for the pipe welding test position designated as 2G.

vertical welding position. The welding position in which the weld axis, at the point of welding, is approximately vertical, and the weld face lies in an approximately vertical plane. See Figures A.8(A) and A.9(B).

vertical-up. A nonstandard term for **uphill.**

V-groove weld. A type of groove weld. See Figures A.5(C), A.5(D), A.5(E), and A.6(C).

virgin flux, *submerged arc welding*. Unused flux that has been produced using new raw materials. See also **recycled flux**.

voltage regulator. An automatic electrical control device for maintaining a constant voltage supply to the primary of a welding transformer.

W

wash pass. A nonstandard term when used for a **cosmetic weld pass** or **cover pass.**

waster plate, *oxyfuel gas cutting*. A carbon steel plate placed on an alloy workpiece at the torch side to provide the necessary iron to facilitate cutting of the alloy workpiece.

water wash. The forcing of exhaust air and fumes from a spray booth through water so that the vented air is free of thermal sprayed particles or fumes.

wave soldering (WS). An automatic soldering process where workpieces are passed through a wave of molten solder. See also **dip soldering.**

wax pattern, *thermite welding*. Wax molded around the workpieces to the form desired for the completed weld.

weave bead. A weld bead formed using weaving. See also **stringer bead.**

weaving. A welding technique in which the energy source is oscillated transversely as it progresses along the weld path. See also **weave bead** and **whipping.**

weld. A localized coalescence of metals or nonmetals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler material.

weld, *v.* The act of welding.

weldability. The capacity of material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service.

weld axis. A line through the length of the weld, perpendicular to and at the geometric center of its cross section. See Figures A.8 and A.9.

weld bead. A weld resulting from a weld pass. See Figures A.12(D) and A.12(E). See also **stringer bead** and **weave bead.**

weld bonding. A resistance spot welding process variation in which the spot weld strength is augmented by adhesive at the faying surfaces.

weld brazing. A joining method that combines resistance welding with brazing.

weld crack. A crack located in the weld metal or heat-affected zone.

weld dam. A metallic or nonmetallic object placed at the end of a weld groove to contain the molten metal and facilitate complete cross sectional filling of the weld groove. See also **runoff weld tab** and **starting weld tab.**

weld dam. A nonstandard term when used for **backing shoe.**

welder. One who performs manual or semiautomatic welding.

welder certification. Written verification that a welder has produced welds meeting a prescribed standard of welder performance.

welder performance qualification. The demonstration of a welder's or welding operator's ability to produce welds meeting prescribed standards.

welder registration. The act of registering a welder certification or a photostatic copy of the welder certification.

weld face. The exposed surface of a weld on the side from which welding was done. See Figures A.13(A) and A.13(E).

weld face underfill. See **underfill.** See Figures A.15(E) and A.15(F).

weld gauge. A device designed for measuring the shape and size of welds.

weld groove, *fusion welding*. A channel in the surface of a workpiece or an opening between two joint members that provides space to contain weld metal.

welding. A joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal. See Figures A.17, A.19, A.20, and A.21.

welding arc. A controlled electrical discharge between the electrode and the workpiece that is formed and sustained by the establishment of a gaseous conductive medium, called an arc plasma.

welding blowpipe. A nonstandard term for **oxyfuel gas welding torch**.

welding current. See **automatic arc welding current** and **resistance welding current**.

welding cycle. The complete series of events involved in the making of a weld.

welding electrode. A component of the welding circuit through which current is conducted and that terminates at the arc, molten conductive slag, or base metal. See also **arc welding electrode, bare electrode, carbon electrode, composite electrode, covered electrode, electroslag welding electrode, emissive electrode, flux cored electrode, lightly coated electrode, metal cored electrode, metal electrode, resistance welding electrode, stranded electrode**, and **tungsten electrode**.

welding filler metal. The metal or alloy to be added in making a weld joint that alloys with the base metal to form weld metal in a fusion welded joint.

welding force. See **dynamic electrode force, electrode force, forge force, friction welding force, static electrode force, theoretical electrode force**, and **upset force**.

welding generator. A generator used for supplying current for welding.

welding ground. A nonstandard and incorrect term for **workpiece connection**.

welding head. The part of a welding machine in which a welding gun or torch is incorporated.

welding helmet. A device equipped with a filter plate designed to be worn on the head to protect eyes, face, and neck from arc radiation, radiated heat, spatter or other harmful matter expelled during some welding and cutting processes.

welding hood. A nonstandard term for **welding helmet**.

welding leads. The workpiece lead and electrode lead of an arc welding circuit.

welding machine. Equipment used to perform the welding operation. For example, spot welding machine, arc welding machine, and seam welding machine.

welding operator. One who operates adaptive control, automatic, mechanized, or robotic welding equipment.

welding position. The relationship between the weld pool, joint, joint members, and welding heat source during welding. See also **flat welding position, horizontal welding position, overhead welding position**, and **vertical welding position**. See Figures A.8, A.9, A.10, and A.11.

welding power source. An apparatus for supplying current and voltage suitable for welding. See also **constant current power source, constant voltage power source, welding generator, welding rectifier**, and **welding transformer**.

welding procedure. The detailed methods and practices involved in the production of a weldment. See also **welding procedure specification**.

welding procedure qualification record (WPQR). A record of welding variables used to produce an acceptable test weldment and the results of tests conducted on the weldment to qualify a welding procedure specification.

welding procedure specification (WPS). A document providing the required welding variables for a specific application to assure repeatability by properly trained welders and welding operators.

welding rectifier. A device in a welding power source for converting alternating current to direct current.

welding rod. A form of welding filler metal, normally packaged in straight lengths, that does not conduct the welding current.

welding schedule. A written statement, usually in tabular form, specifying values of parameters and the welding sequence for performing a welding operation.

welding sequence. The order of making welds in a weldment.

welding symbol. A graphical representation of the specifications for producing a welded joint. See also **weld symbol**. For examples and rules for application, refer to *Standard Symbols for Welding, Brazing and Nondestructive Examination,* ANSI/AWS A2.4.[6]

welding technique. The details of a welding procedure that are controlled by the welder or welding operator.

6. American Welding Society (AWS) Committee on Definitions and Symbols, *Standard Symbols for Welding, Brazing and Nondestructive Examination*, ANSI/AWS A2.4, Miami: American Welding Society.

welding test position. The orientation of a weld joint for welding procedure or welder qualification testing. See also **welding test position designation.**

welding test position designation. A symbol representation for a fillet weld or a groove weld, the joint orientation and the welding test position. See **1F, 2F, 2FR, 3F, 4F, 5F, 6F, 1G, 2G, 3G, 4G, 5G, 6G,** and **6GR.**

welding tip, *oxyfuel gas welding*. That part of an oxyfuel gas welding torch from which gases issue.

welding tip. A nonstandard term when used for **resistance welding electrode** for resistance spot welding.

welding torch. See **gas tungsten arc welding torch, oxyfuel gas welding torch,** and **plasma arc welding torch.**

welding transformer. A transformer used for supplying current for welding.

welding voltage. See **arc voltage, open circuit voltage** and **resistance welding voltage.**

welding wheel. A nonstandard term for **resistance welding electrode.**

welding wire. A form of welding filler metal, normally packaged as coils or spools, that may or may not conduct electrical current depending upon the welding process with which it is used. See also **welding electrode** and **welding rod.**

weld interface. The interface between weld metal and base metal in a fusion weld, between base metals in a solid-state weld without filler metal, or between filler metal and base metal in a solid-state weld with filler metal.

weld interval, *resistance welding*. The total of all heat and cool times, and upslope time, used in making one multiple-impulse weld. See also **weld time.**

weld joint mismatch. Misalignment of the joint members.

weld line. A nonstandard term for **weld interface.**

weldment. An assembly whose component parts are joined by welding.

weld metal. Metal in a fusion weld consisting of that portion of the base metal and filler metal melted during welding. See also **mixed zone** and **unmixed zone.**

weld metal zone (WMZ). That portion of the weld area consisting of weld metal. See Figure A.13(G).

weld metal crack. A crack occurring in the weld metal zone. See Figure A.16.

weldor. A nonstandard term for **welder.**

weld pass. A single progression of welding along a joint. The result of a weld pass is a weld bead or layer.

weld pass sequence. The order in which the weld passes are made. See **cross-sectional sequence** and **longitudinal sequence.**

weld penetration. A nonstandard term for **joint penetration** or **root penetration.**

weld pool. The localized volume of molten metal in a weld prior to its solidification as weld metal.

weld puddle. A nonstandard term for **weld pool.**

weld recognition. A function of an adaptive control that determines changes in the shape of the weld pool or the weld metal during welding, and directs the welding machine to take appropriate action. See also **joint recognition** and **joint tracking.**

weld reinforcement. Weld metal in excess of the quantity required to fill a weld groove. See also **convexity, face reinforcement,** and **root reinforcement.**

weld root. The points, shown in cross section, at which the weld metal intersects the base metal and extends furthest into the weld joint. See Figures A.13(B), A.13(D), A.13(E), A.13(H), A.13(I), A.13(J), A.13(K), A.13(M), A.13(N), A.13(O), and A.13(P).

weld seam. A nonstandard term for **joint, seam weld, weld,** or **weld joint.**

weld shoe. A nonstandard term when used for **backing shoe.**

weld size. See **edge weld size, fillet weld size, groove weld size, plug weld size, projection weld size, seam weld size, slot weld size** and **spot weld size.**

weld symbol. A graphic character connected to the reference line of a welding symbol specifying the weld type. For examples and rules for application, refer to *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, ANSI/AWS A2.4.[7]

7. See Reference 6.

weld tab. Additional material that extends beyond either end of the joint, on which the weld is started or terminated. See **runoff weld tab** and **starting weld tab**.

weld throat. See **actual throat**, **effective throat**, and **theoretical throat.**

weld time. See **automatic arc welding weld time** and **resistance welding weld time**.

weld toe. The junction of the weld face and the base metal. See Figures A.13(A) and A.13(E).

weld voltage. See **arc voltage**.

wetting. The phenomenon whereby a liquid filler metal or flux spreads and adheres in a thin continuous layer on a solid base metal.

whipping. A manual welding technique in which the arc or flame is oscillated backwards and forwards in the direction of travel as it progresses along the weld path. See also **oscillation** and **weaving.**

wiped joint. A joint made with solder having a wide melting range and with the heat supplied by the molten solder poured onto the joint. The solder is manipulated with a hand-held cloth or paddle so as to obtain the required size and contour.

wire feed speed. The rate at which wire is consumed in arc cutting, thermal spraying, or welding.

wire flame spraying (FLSP-W). A thermal spraying process variation in which the surfacing material is in wire form.

wire straightener. A device used for controlling the cast and helix of coiled wire to enable it to be easily fed through the wire feed system.

work angle. The angle less than 90° between a line perpendicular to the major workpiece surface and a plane determined by the electrode axis and the weld axis. In a T-joint or a corner joint, the line is perpendicular to the nonbutting member. This angle can also be used to partially define the position of guns, torches, rods, and beams. See also **drag angle, push angle,** and **travel angle**.

work angle, *pipe*. The angle less than 90° between a line that is perpendicular to the cylindrical pipe surface at the point of intersection of the weld axis and the extension of the electrode axis, and a plane determined by the electrode axis and a line tangent to the pipe at the same point. In a T-joint, the line is perpendicular to the nonbutting member. This angle can also be used to partially define the position of guns, torches, rods, and beams. See also **drag angle, push angle,** and **travel angle**.

work coil. See **induction work coil**.

work connection. A nonstandard term for **workpiece connection.**

work lead. A nonstandard term for **workpiece lead**.

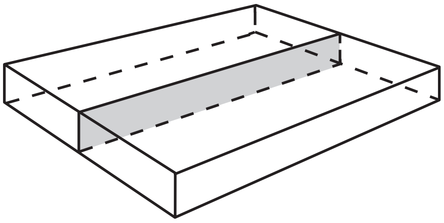
workpiece. The part that is welded, brazed, soldered, thermal cut, or thermal sprayed.

workpiece connection. The connection of the workpiece lead to the workpiece.

workpiece lead. The electrical conductor between the arc welding current source and workpiece connection.

wormhole porosity. A nonstandard term when used for **piping porosity.**

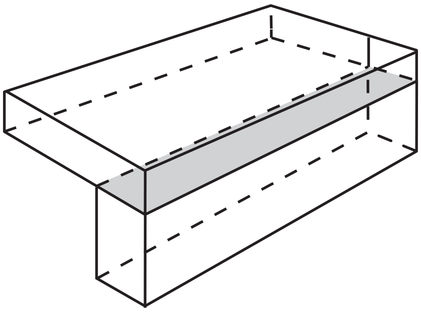
FIGURES



APPLICABLE WELDS

BEVEL-GROOVE	SQUARE GROOVE
FLARE-BEVEL-GROOVE	U-GROOVE
FLARE-V-GROOVE	V-GROOVE
J-GROOVE	BRAZE

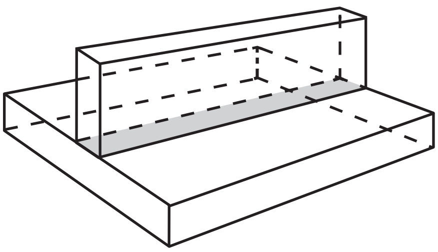
(A) BUTT JOINT



APPLICABLE WELDS

FILLET	V-GROOVE
BEVEL-GROOVE	PLUG
FLARE-BEVEL-GROOVE	SLOT
FLARE-V-GROOVE	SPOT
J-GROOVE	SEAM
SQUARE-GROOVE	PROJECTION
U-GROOVE	BRAZE

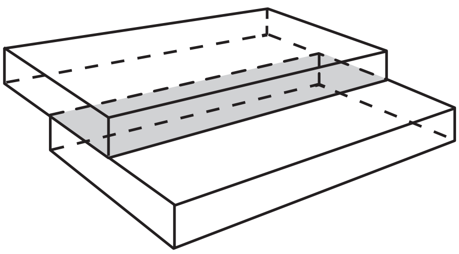
(B) CORNER JOINT



APPLICABLE WELDS

FILLET	SLOT
BEVEL-GROOVE	SPOT
FLARE-BEVEL-GROOVE	SEAM
J-GROOVE	PROJECTION
SQUARE-GROOVE	BRAZE
PLUG	

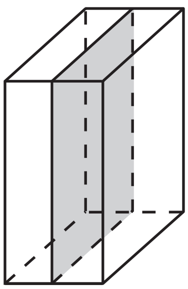
(C) T-JOINT



APPLICABLE WELDS

FILLET	SLOT
BEVEL-GROOVE	SPOT
FLARE-BEVEL-GROOVE	SEAM
J-GROOVE	PROJECTION
PLUG	BRAZE

(D) LAP JOINT



APPLICABLE WELDS

BEVEL-GROOVE	V-GROOVE
FLARE-BEVEL-GROOVE	EDGE
FLARE-V-GROOVE	SEAM
J-GROOVE	SPOT
SQUARE-GROOVE	PROJECTION
U-GROOVE	BRAZE

(E) EDGE JOINT

Figure A.1—Joints Types

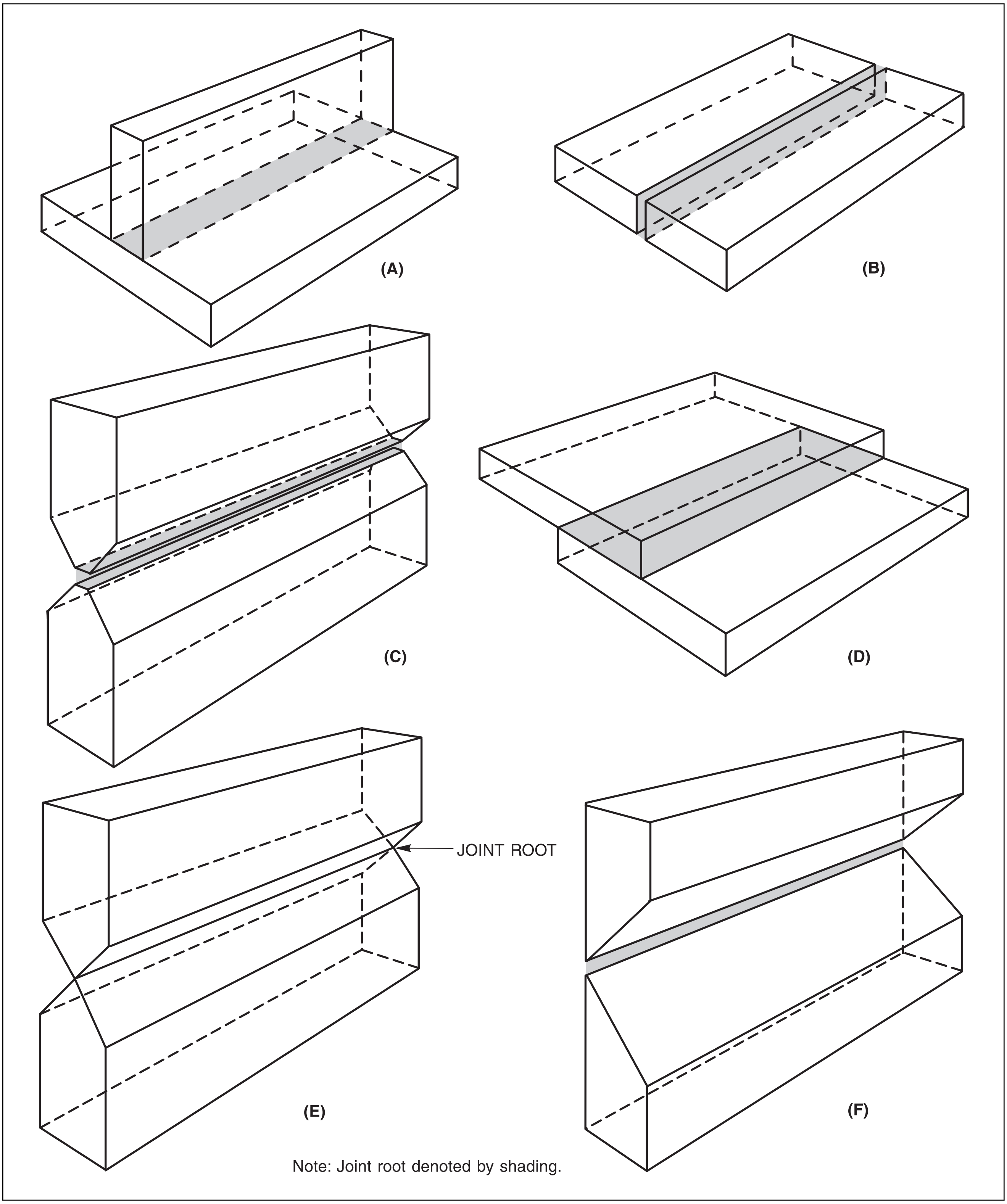


Figure A.2—Joint Root

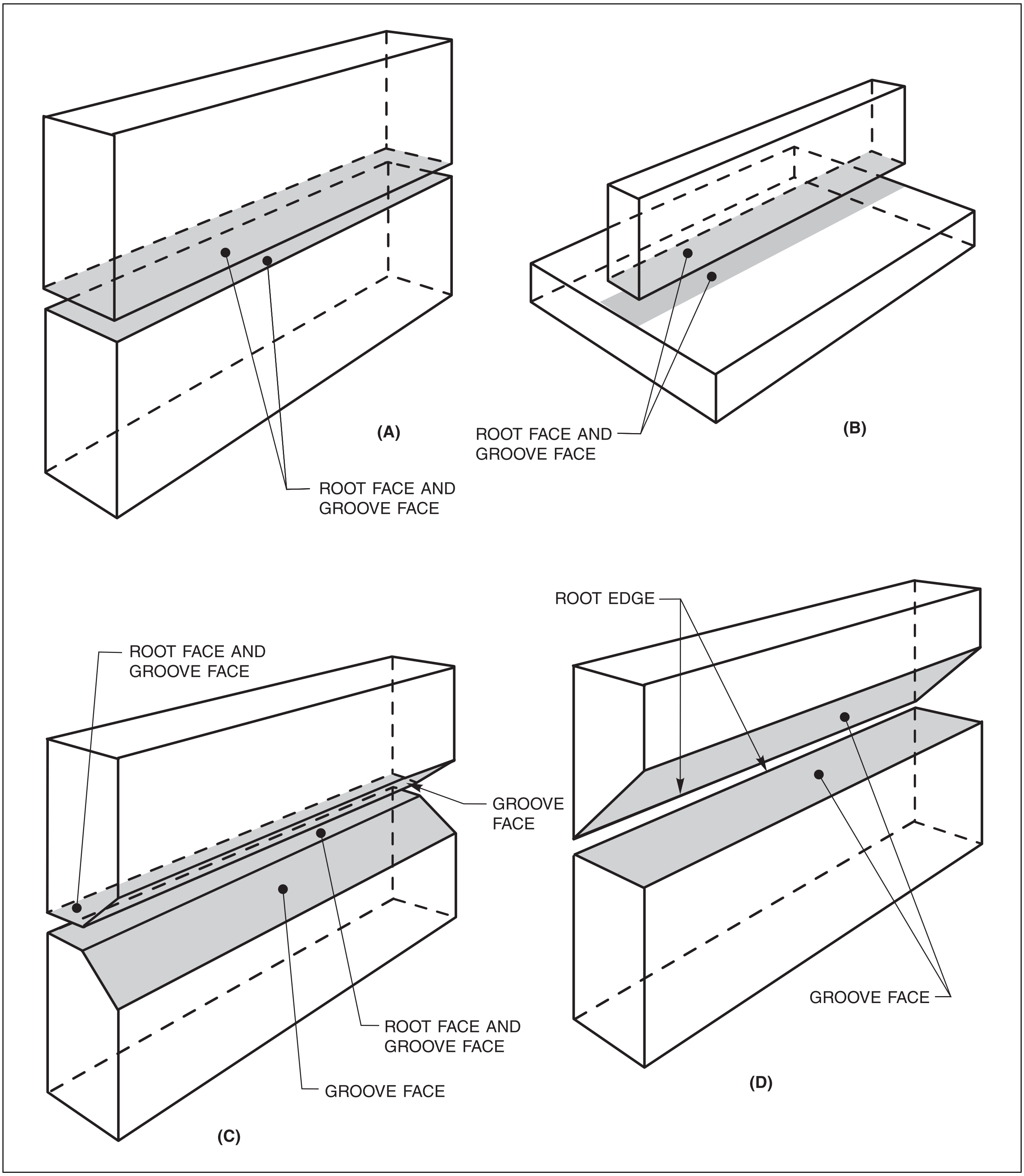


Figure A.3—Groove Face, Root Edge, and Root Face

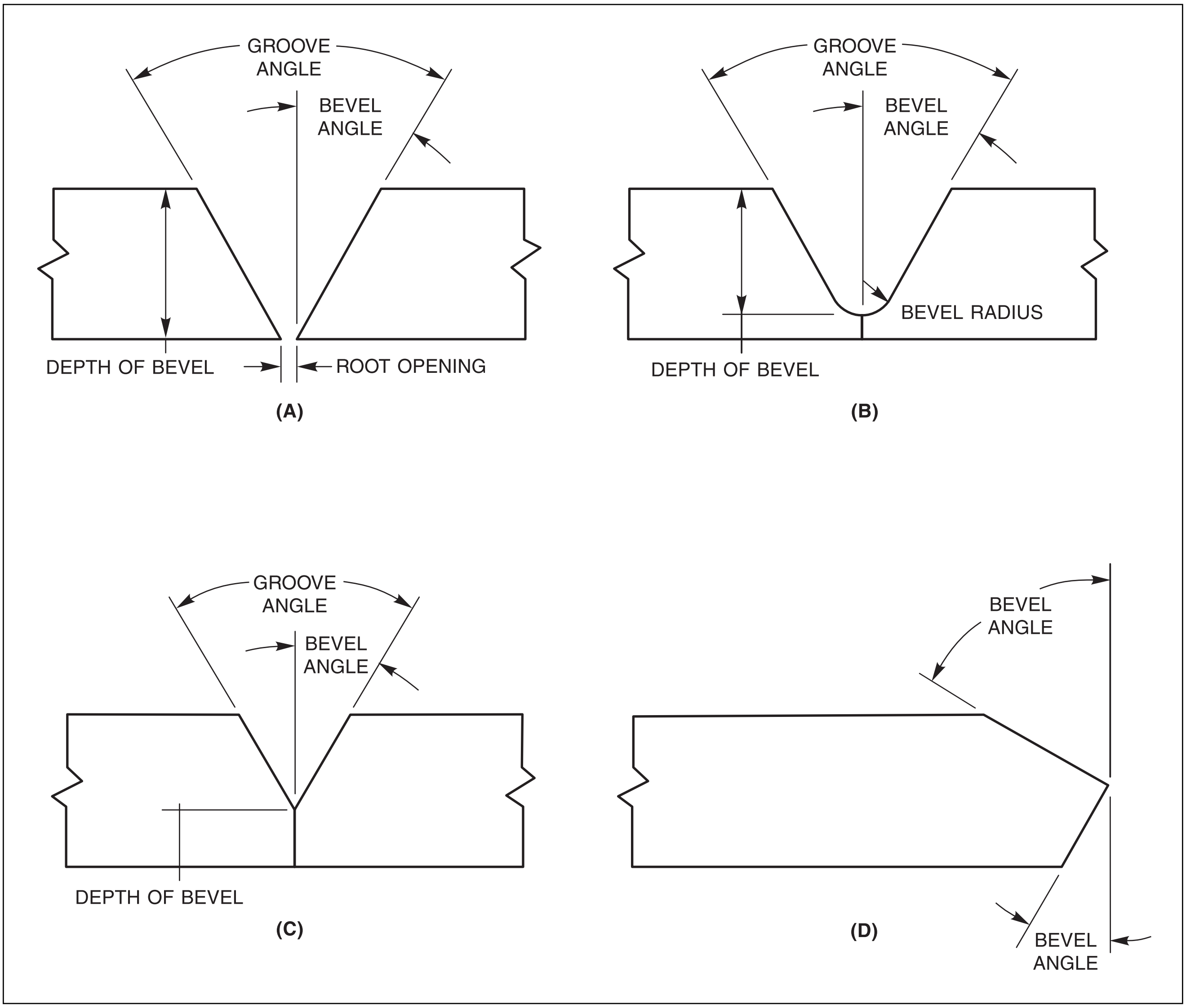


Figure A.4—Bevel Angle, Depth of Bevel, Groove Angle, Groove Radius, Root Opening, and Bevel Face

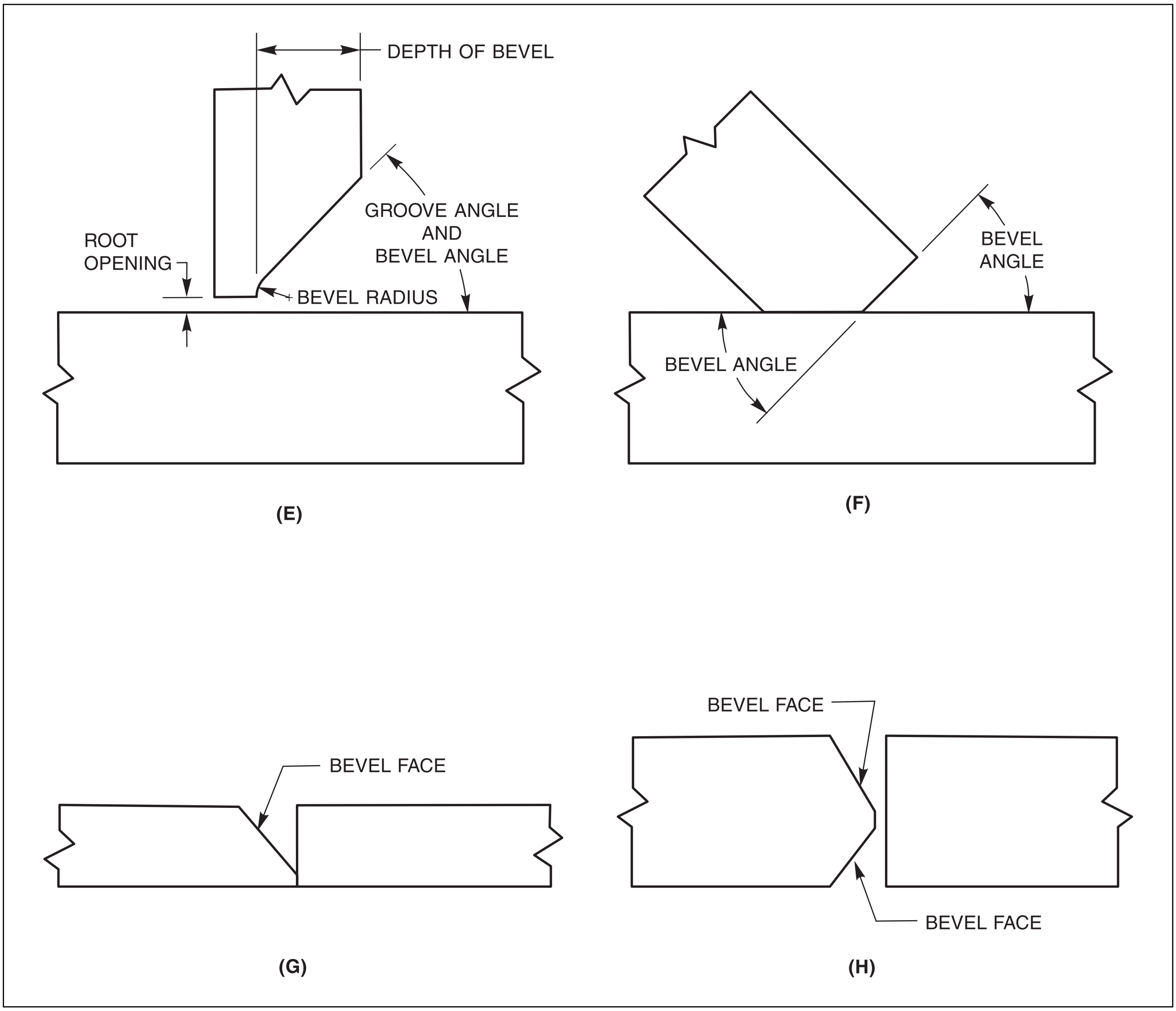


Figure A.4 (Continued)—Bevel Angle, Depth of Bevel, Groove Angle, Groove Radius, Root Opening, and Bevel Face

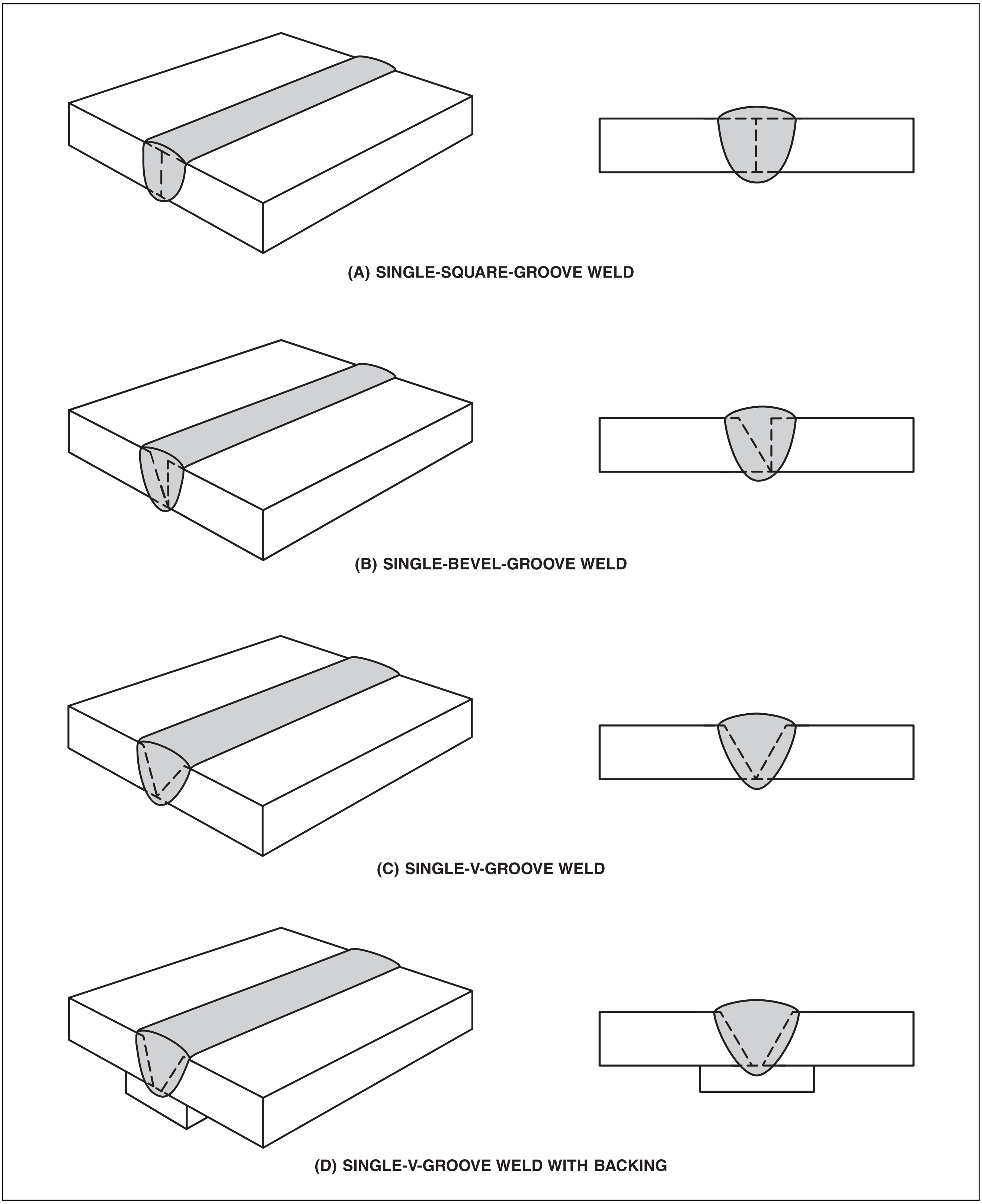
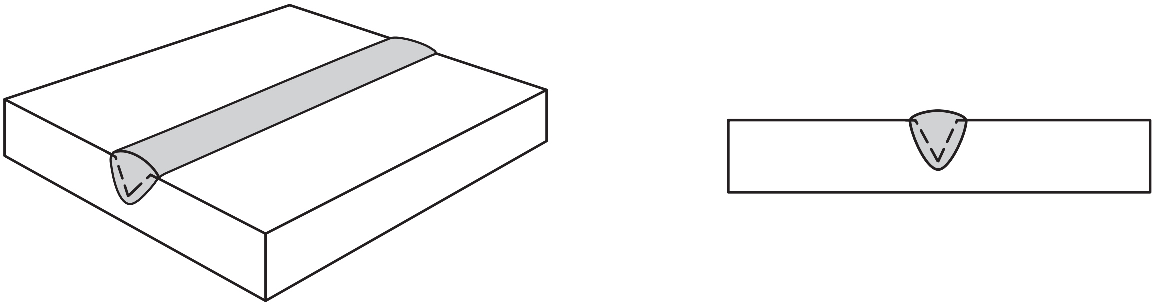
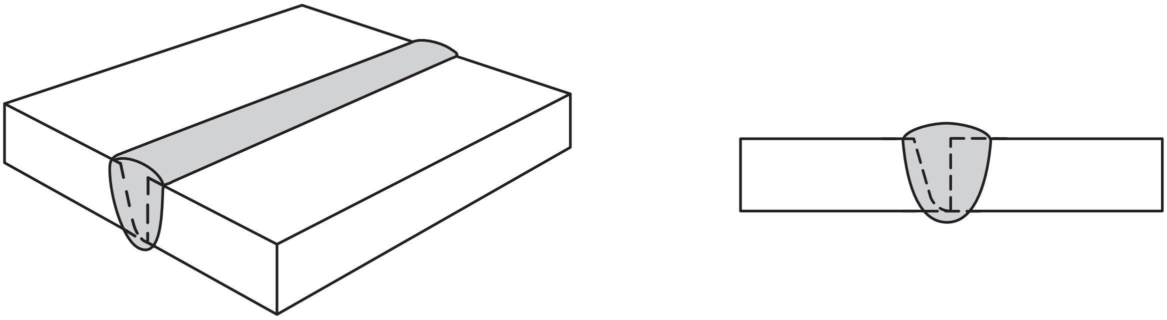


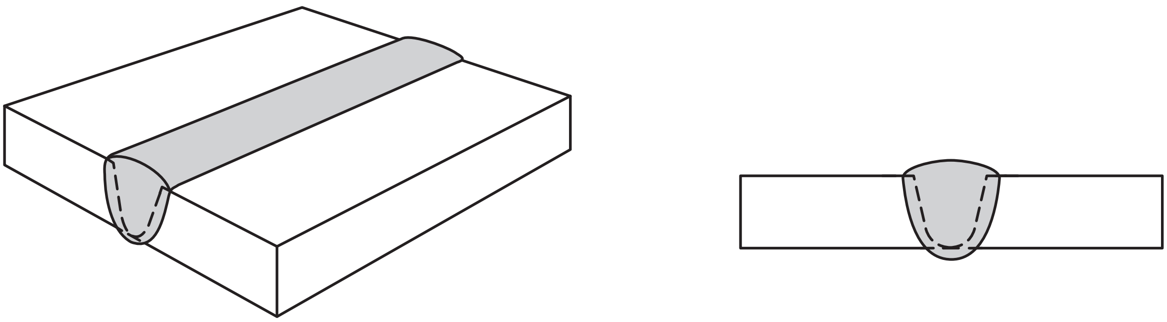
Figure A.5—Single-Groove Weld Joints



(E) SINGLE-V-GROOVE WELD ON A SURFACE



(F) SINGLE-J-GROOVE WELD



(G) SINGLE-U-GROOVE WELD

Figure A.5 (Continued)—Single-Groove Weld Joints

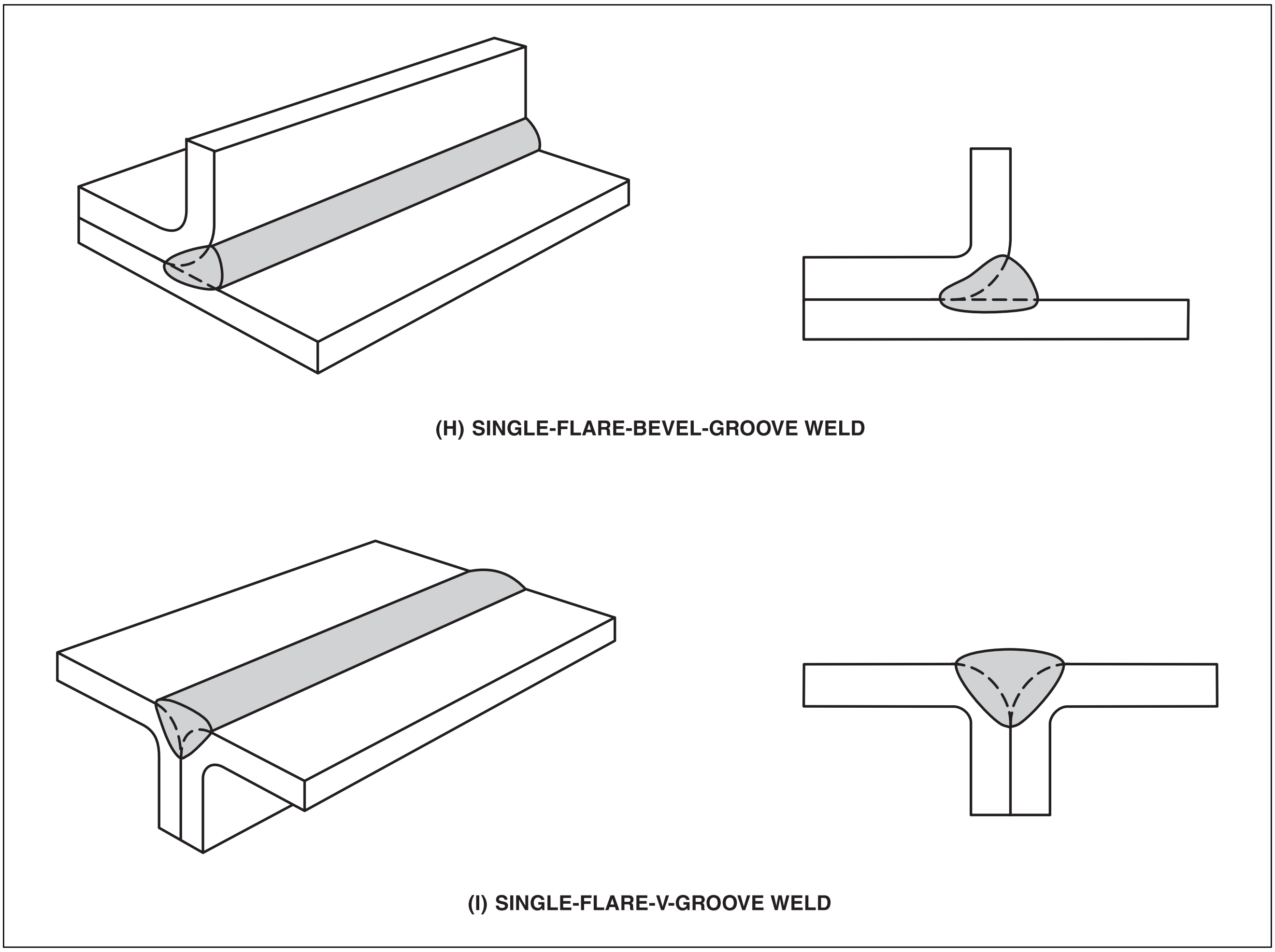


Figure A.5 (Continued)—Single-Groove Weld Joints

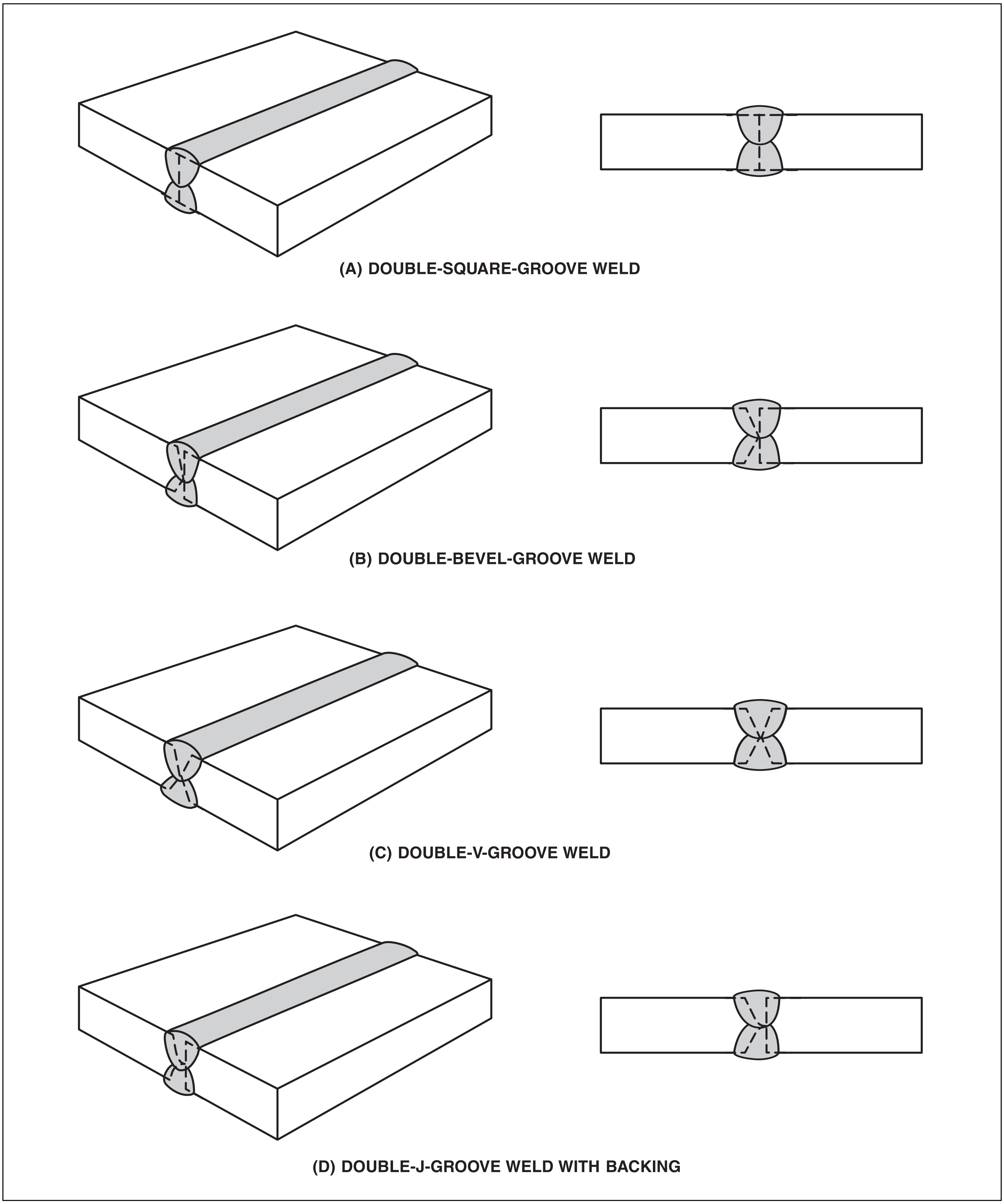
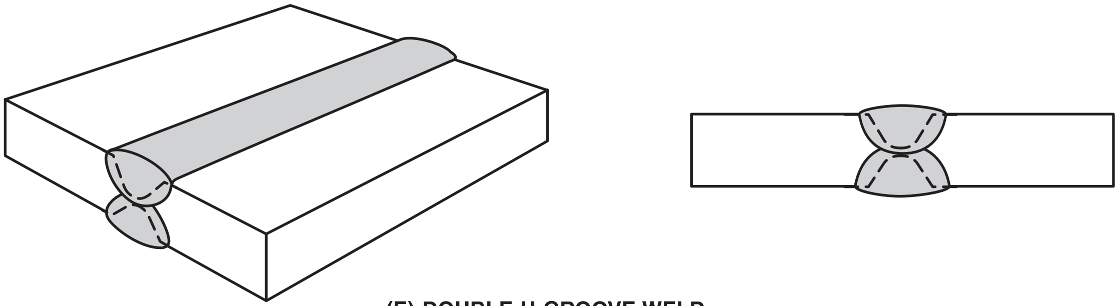
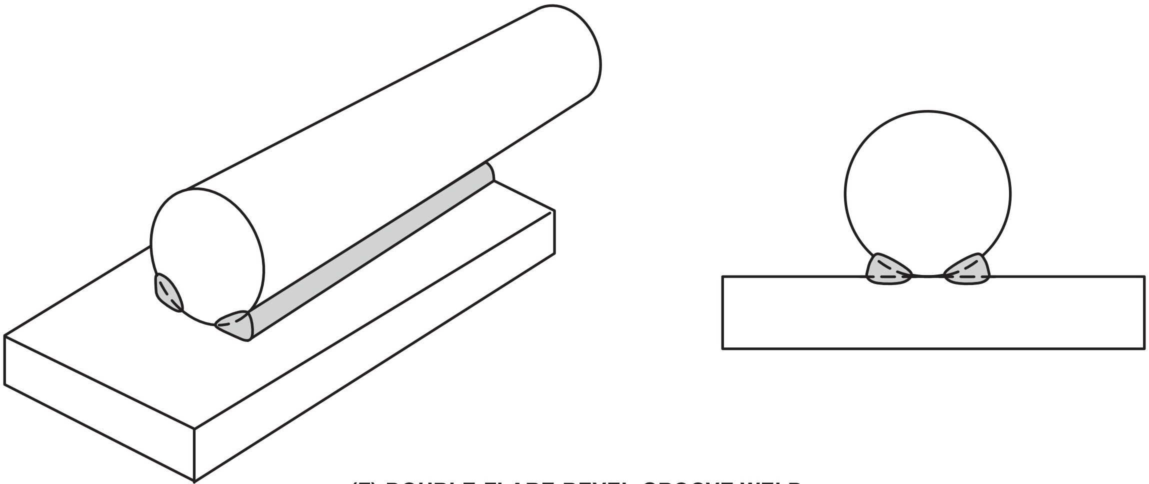


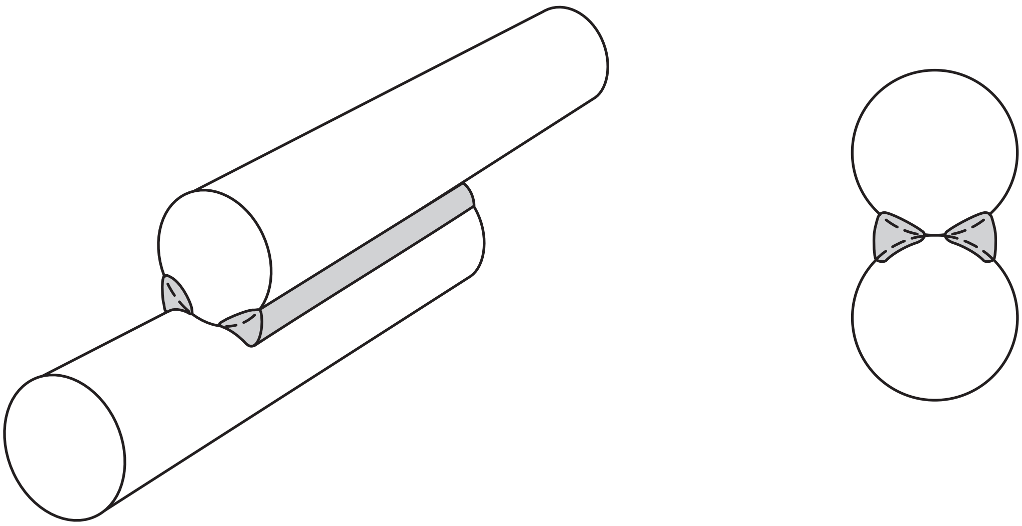
Figure A.6—Double-Groove Weld Joints



(E) DOUBLE-U-GROOVE WELD



(F) DOUBLE-FLARE-BEVEL-GROOVE WELD



(G) DOUBLE-FLARE-V-GROOVE WELD

Figure A.6 (Continued)—Double-Groove Weld Joints

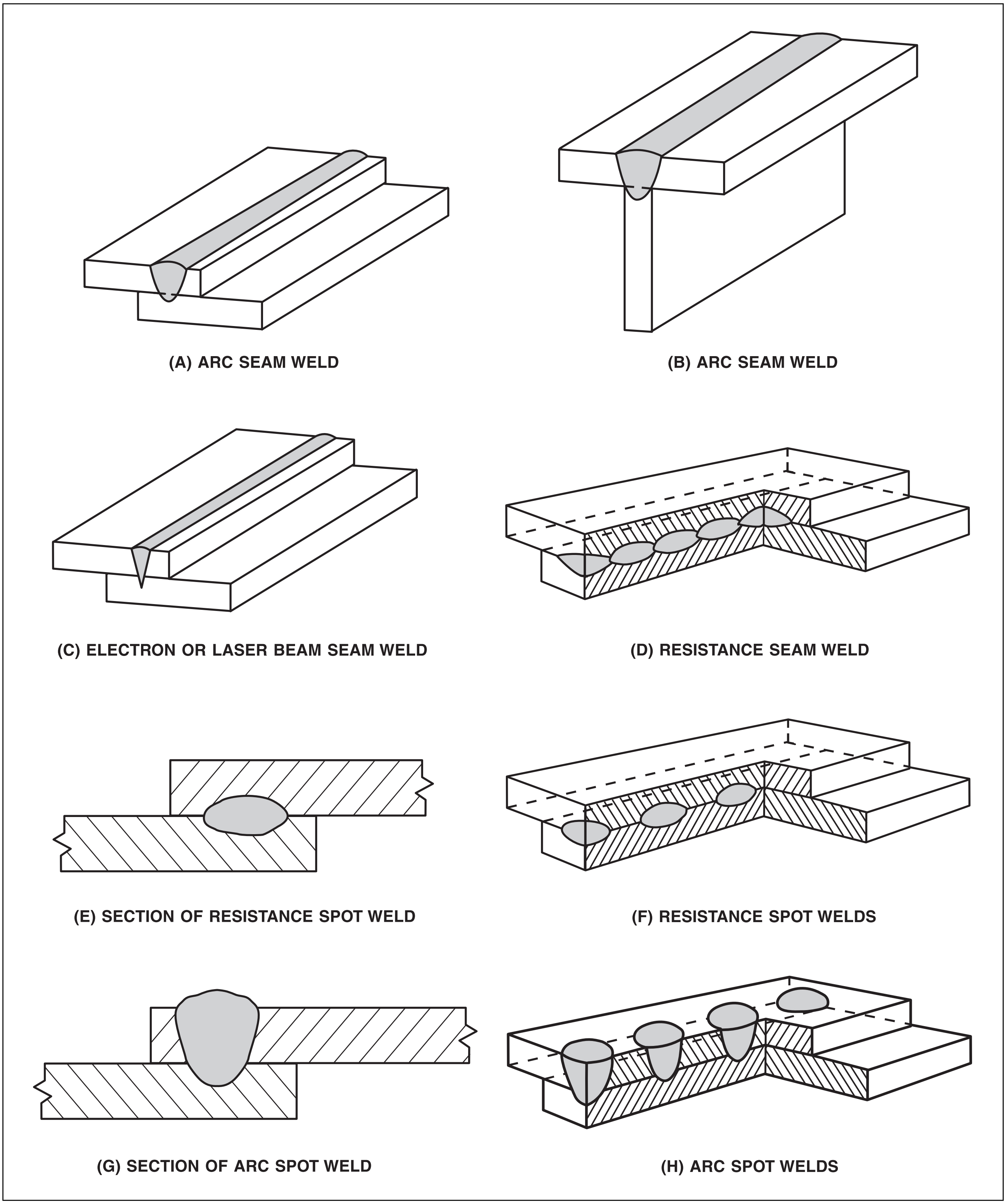
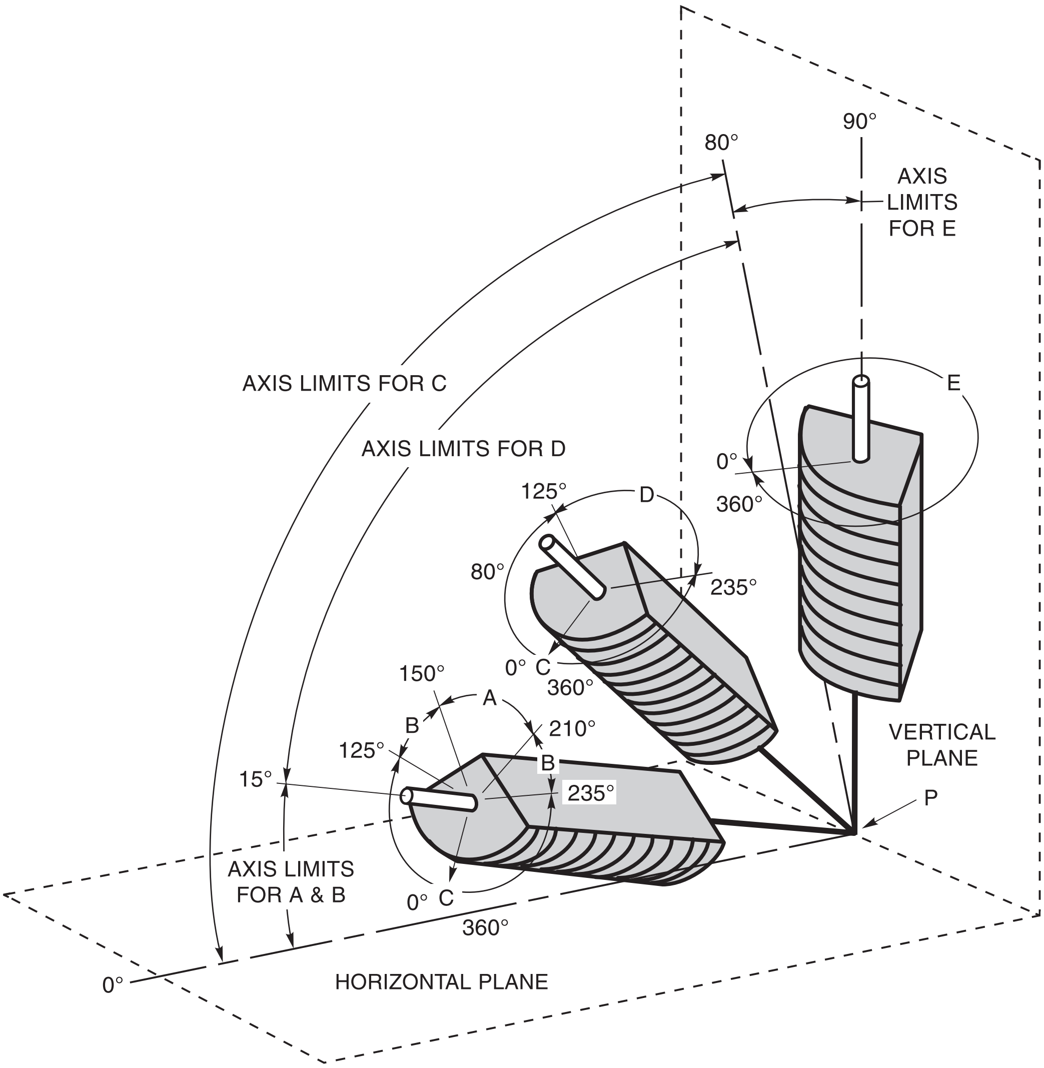


Figure A.7—Seam Welds and Spot Welds

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 E	15° to 80° 80° to 90°	80° to 280° 0° to 360°

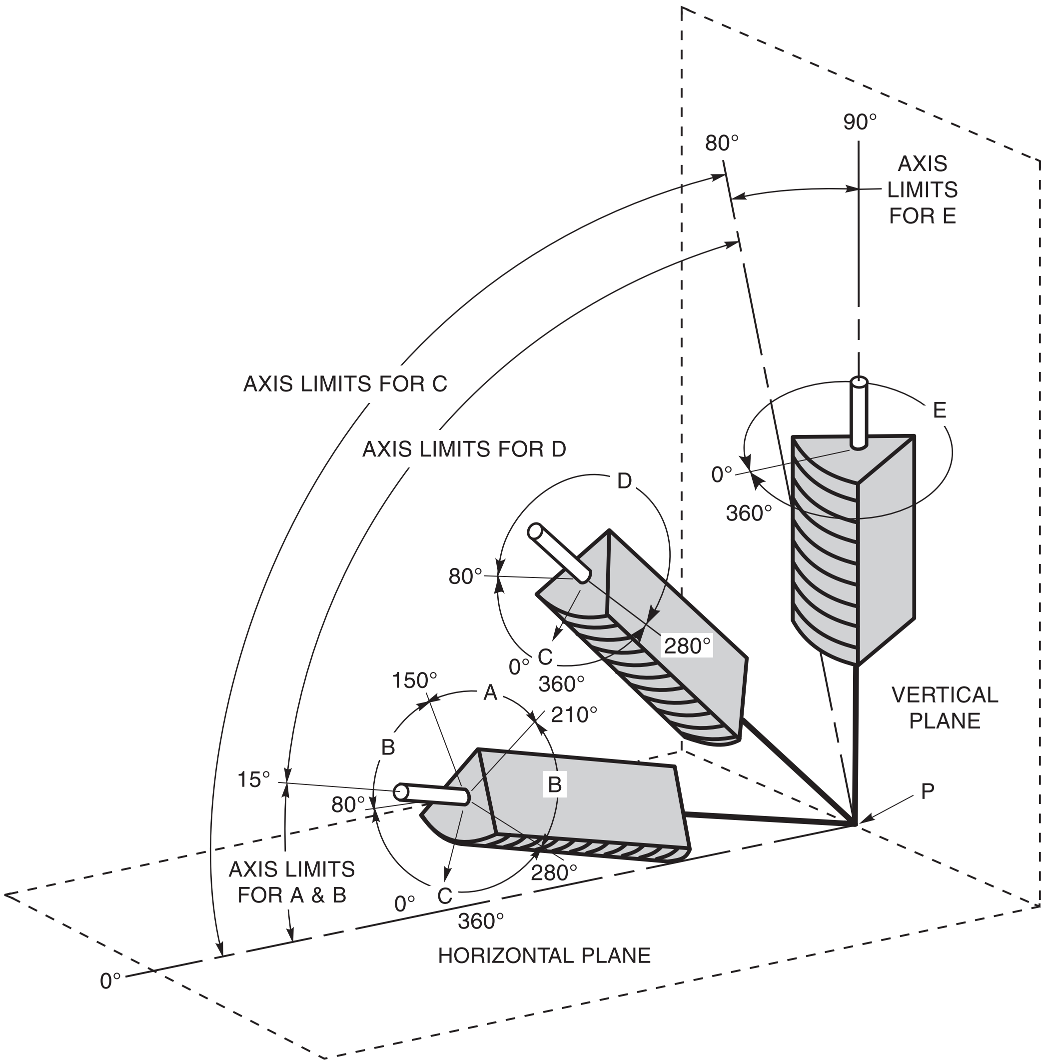


Notes:

1. The horizontal reference plane is always taken to lie below the weld under consideration.
2. The inclination of the weld axis is measured from the horizontal reference plane toward the vertical reference plane.
3. The angle of rotation of the weld face is determined by a line perpendicular to the weld face at its center which passes through the weld axis. The reference position (0°) of rotation of the weld 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 weld face is measured in a clockwise direction from the reference position (0°).

Figure A.8—Welding Position Diagram for Groove Welds in Plate

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 E	15° to 80° 80° to 90°	125° to 235° 0° to 360°



Notes:
1. The horizontal reference plane is always taken to lie below the weld under consideration.
2. The inclination of the weld axis is measured from the horizontal reference plane toward the vertical reference plane.
3. The angle of rotation of the weld face is determined by a line perpendicular to the weld face at its center which passes through the weld axis. The reference position (0°) of rotation of the weld 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 weld face is measured in a clockwise direction from the reference position (0°).

Figure A.9—Welding Position Diagram for Fillet Welds in Plate

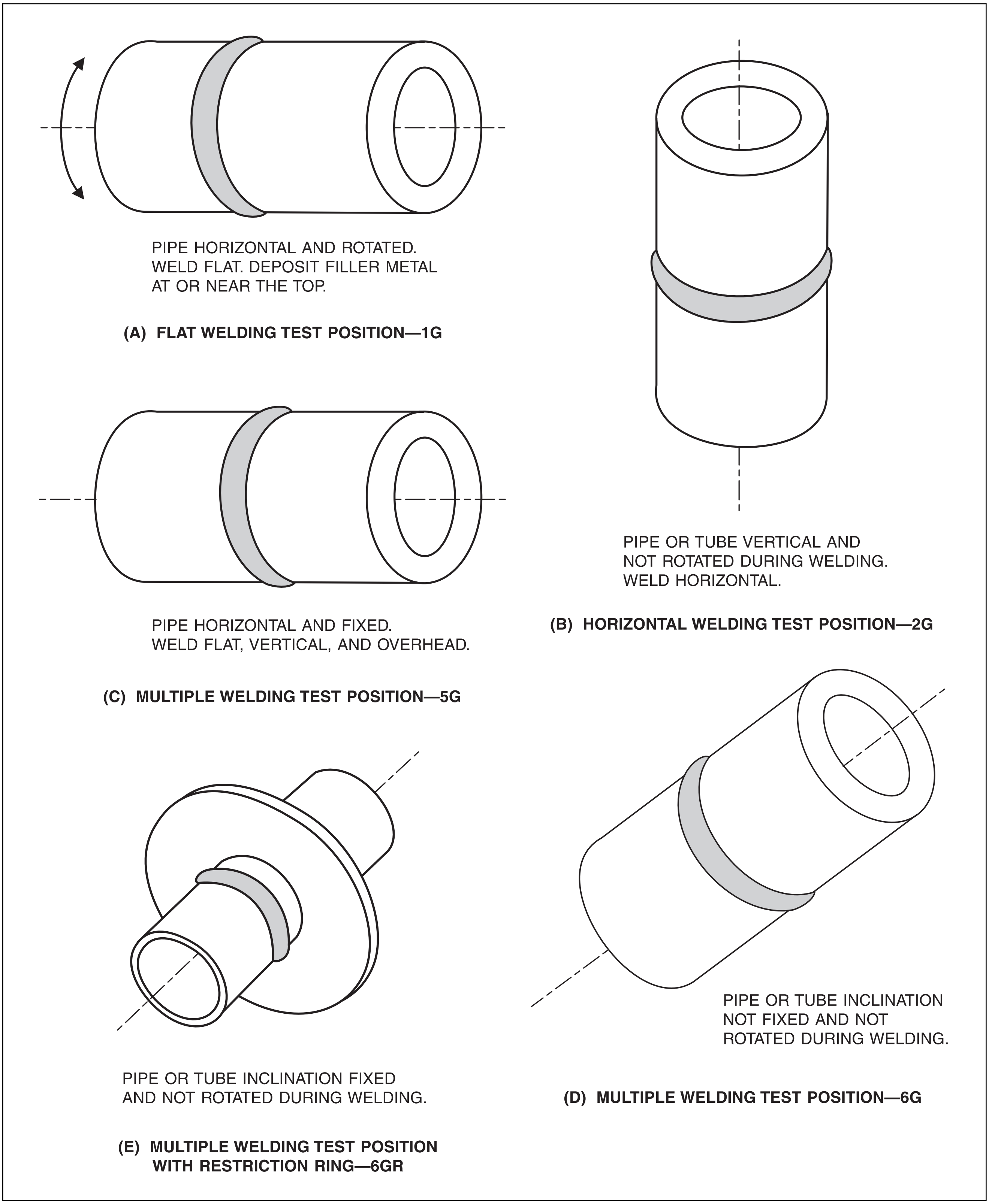


Figure A.10—Welding Test Positions and Their Designations for Groove Welds in Pipe

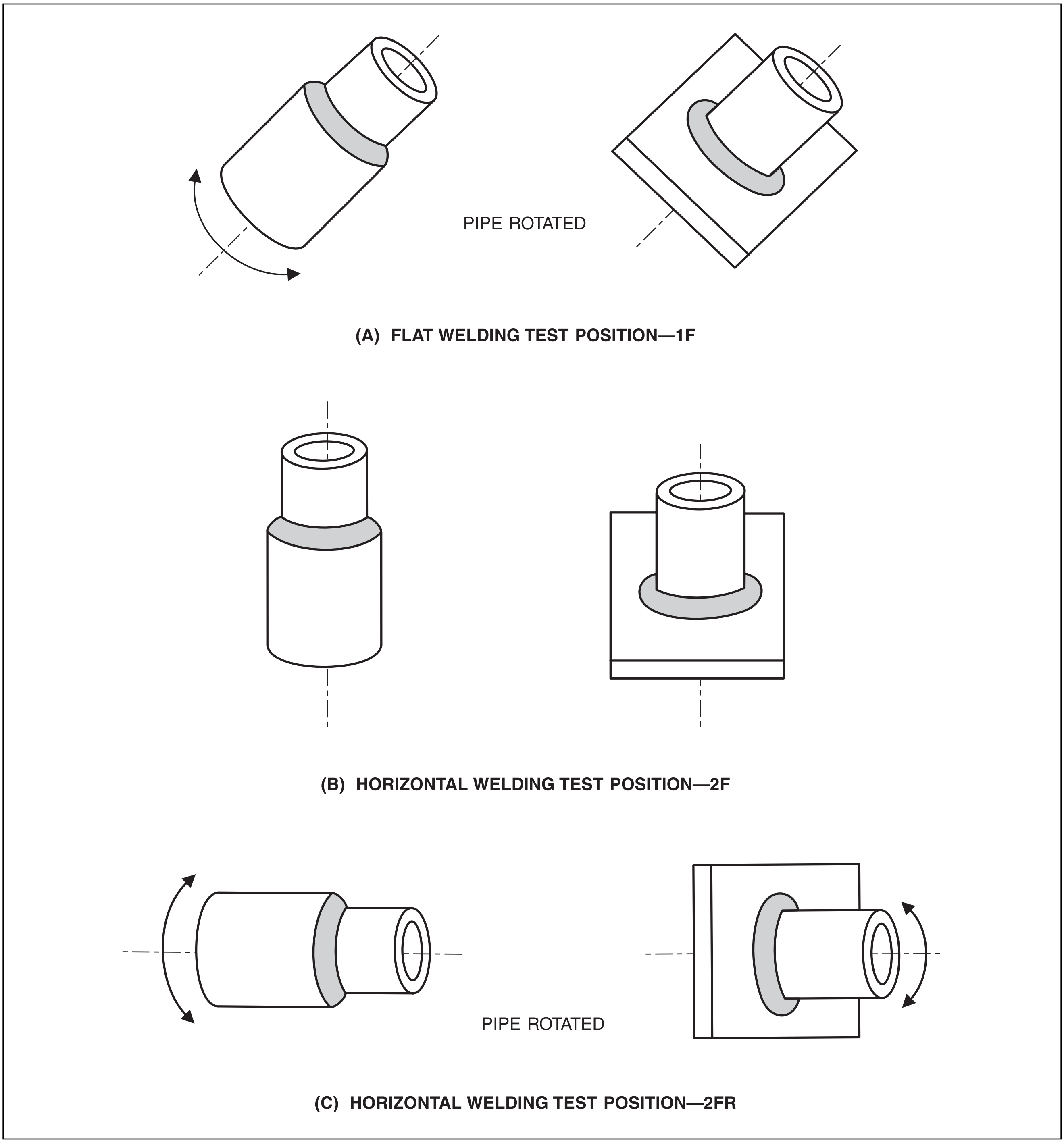
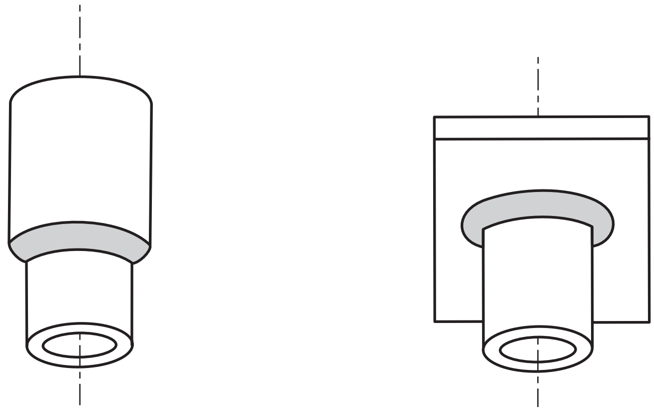
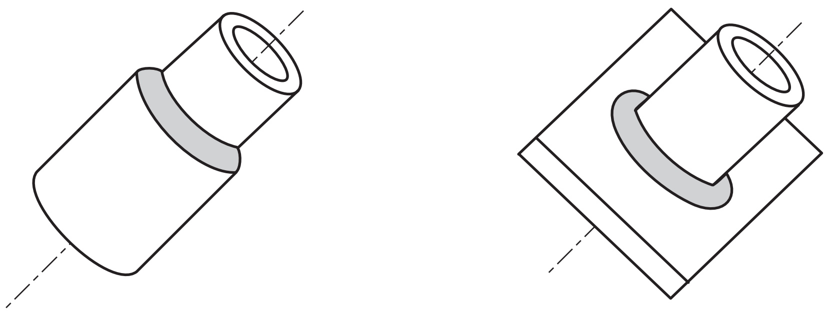


Figure A.11—Welding Test Positions and Their Designations for Fillet Welds in Pipe



(D) OVERHEAD WELDING TEST POSITION—4F

(E) MULTIPLE WELDING TEST POSITION—5F



(F) MULTIPLE WELDING TEST POSITION—6F

Figure A.11 (Continued)—Welding Test Positions and Their Designations for Fillet Welds in Pipe

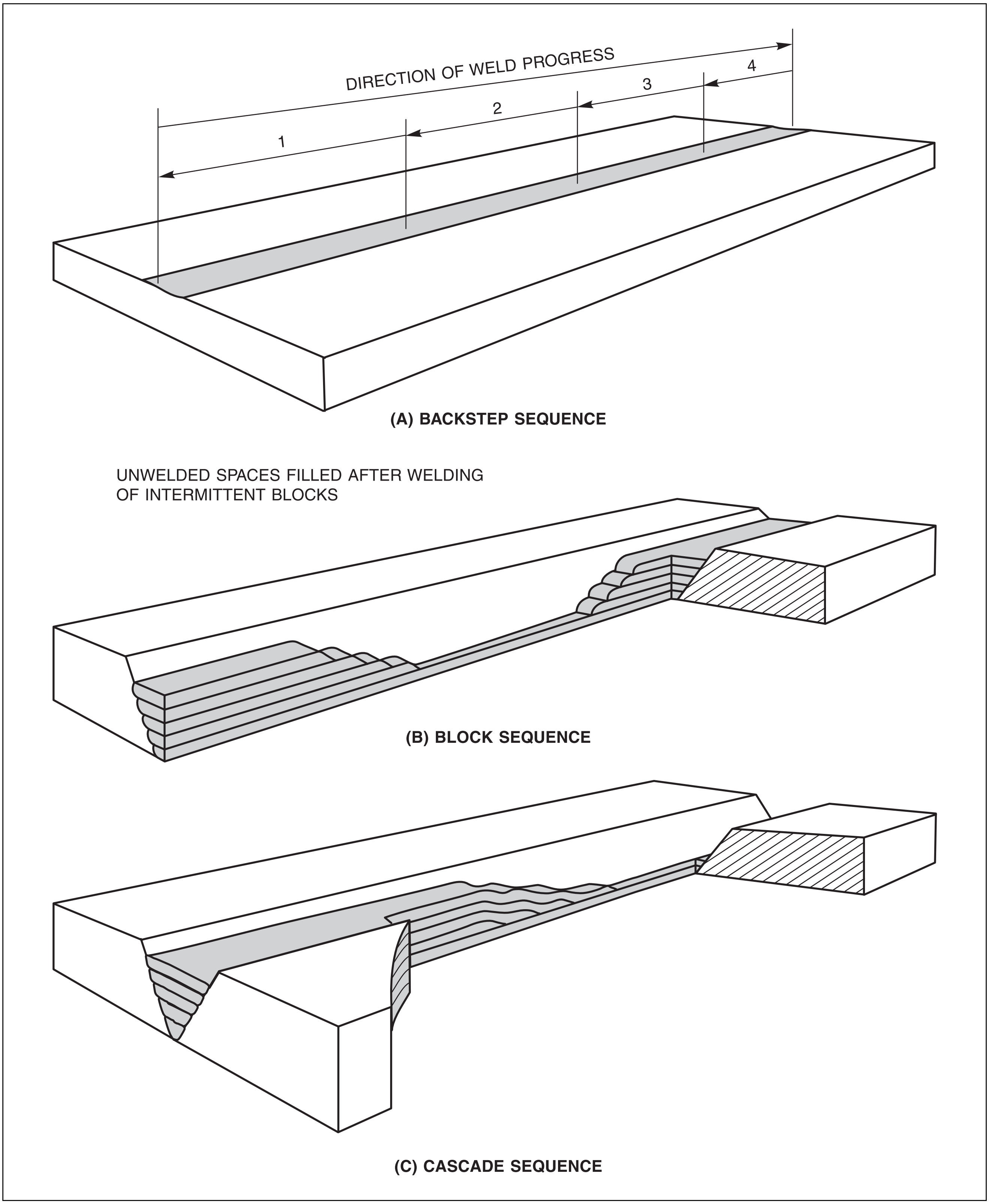
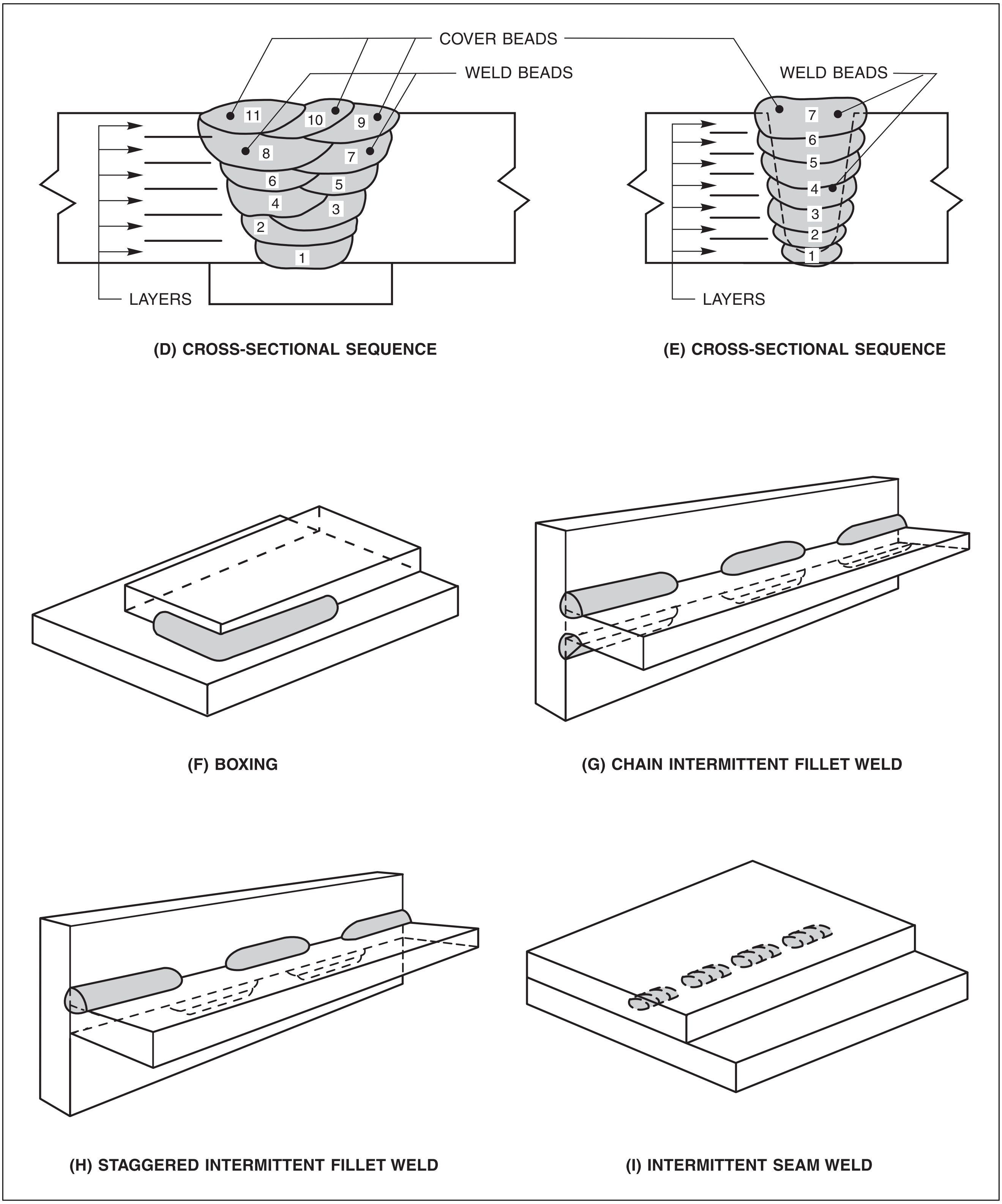


Figure A.12—Welding Sequence



(D) CROSS-SECTIONAL SEQUENCE

(E) CROSS-SECTIONAL SEQUENCE

(F) BOXING

(G) CHAIN INTERMITTENT FILLET WELD

(H) STAGGERED INTERMITTENT FILLET WELD

(I) INTERMITTENT SEAM WELD

Figure A.12 (Continued)—Welding Sequence

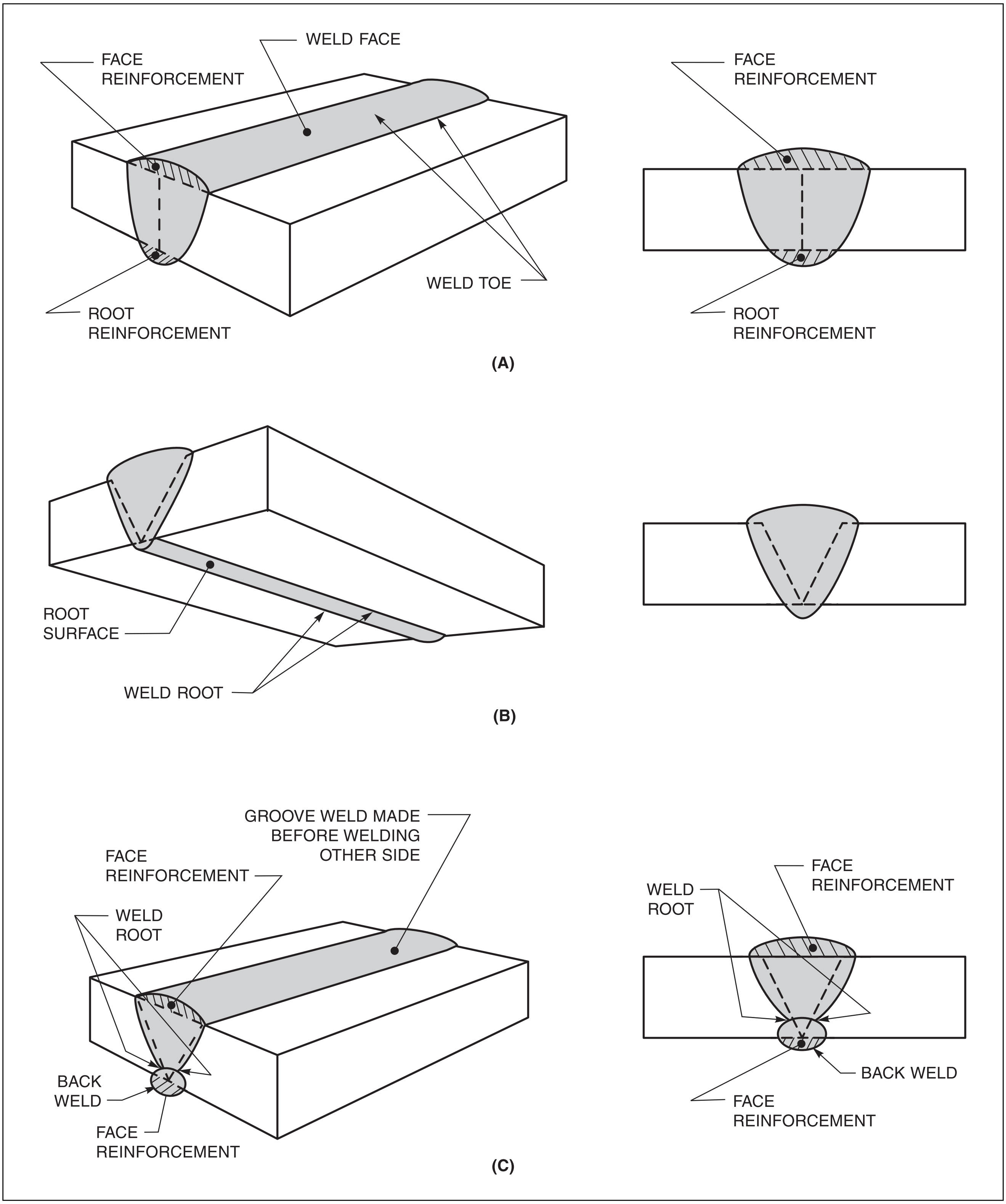


Figure A.13—Parts of a Weld

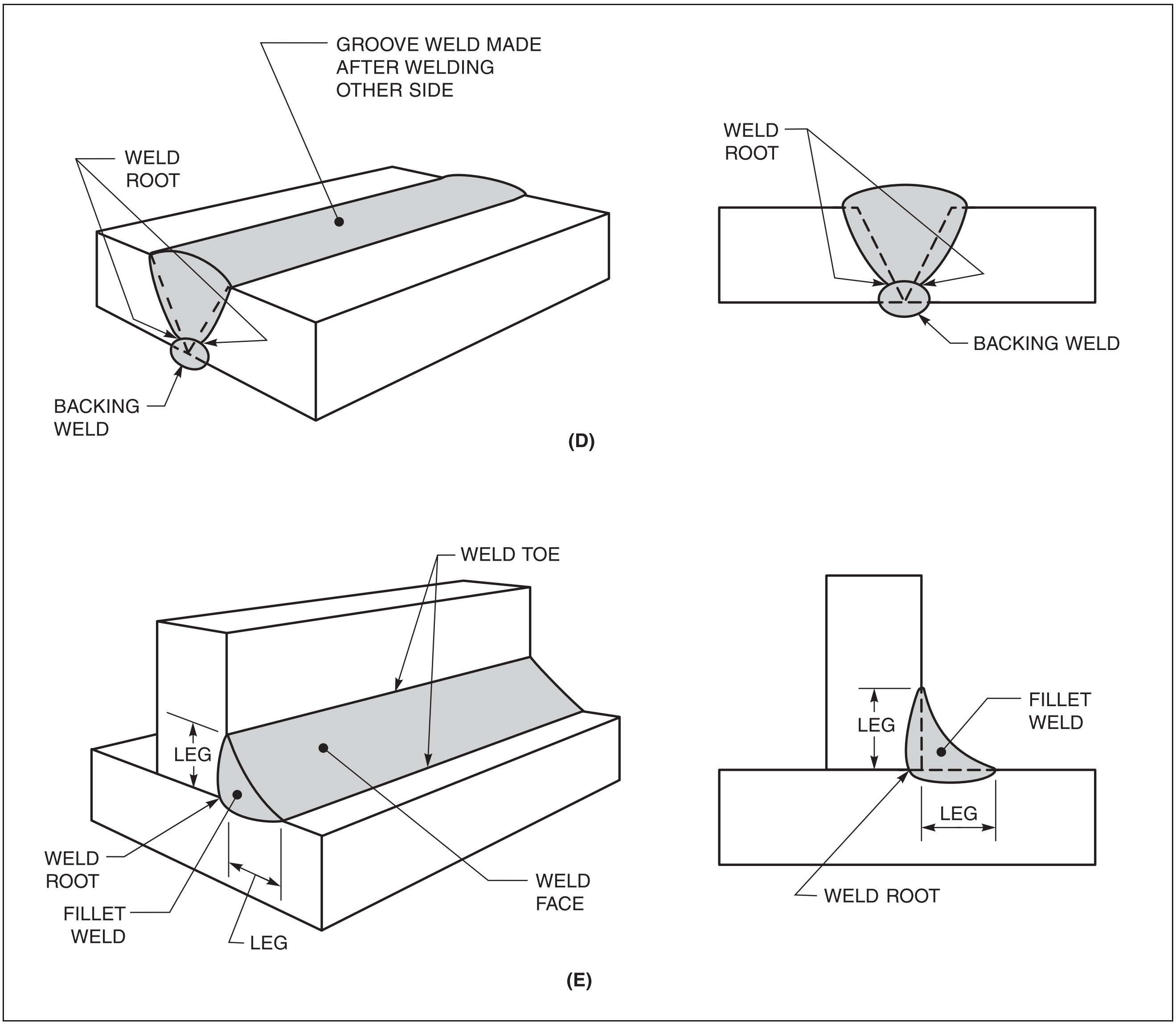


Figure A.13 (Continued)—Parts of a Weld

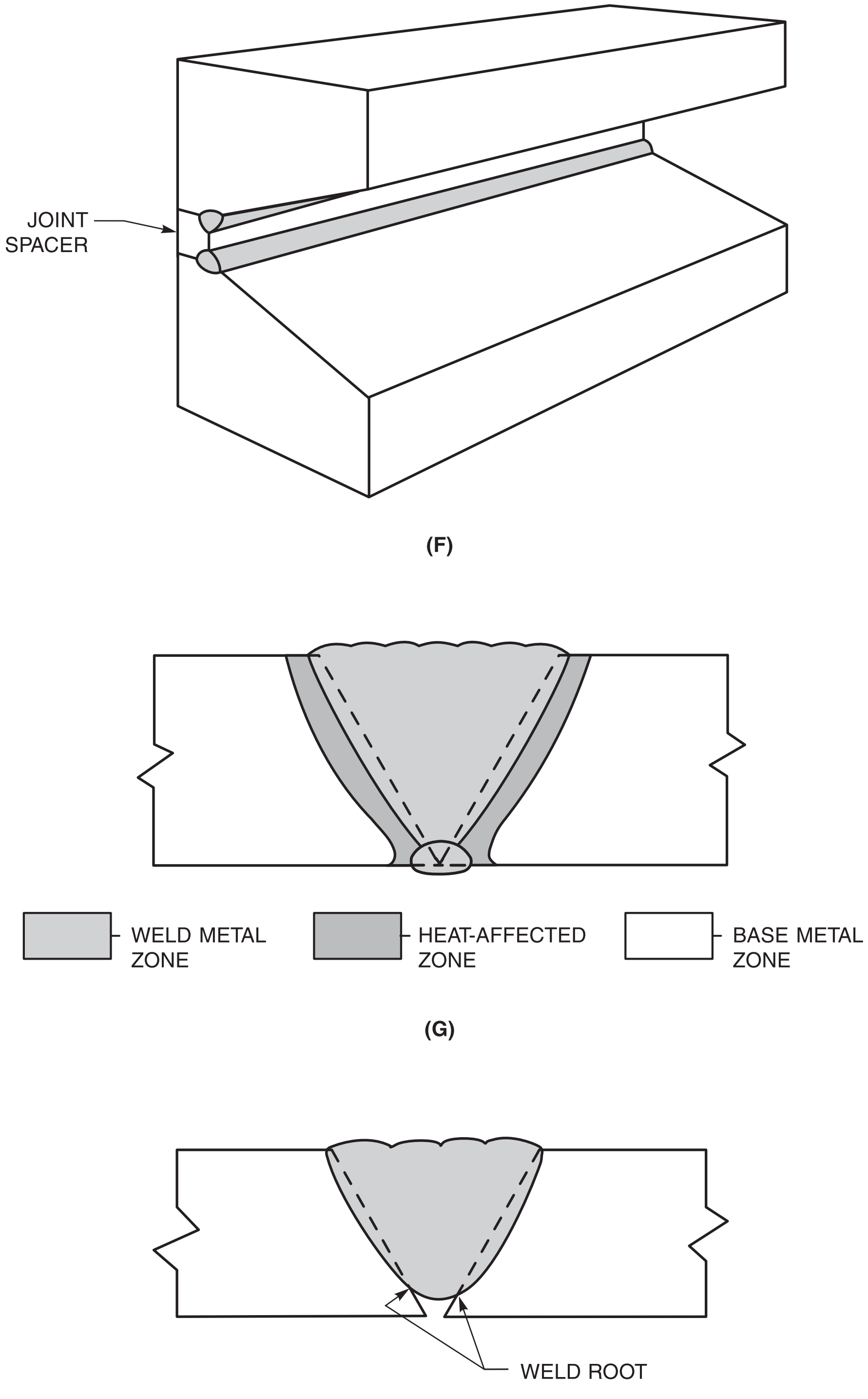
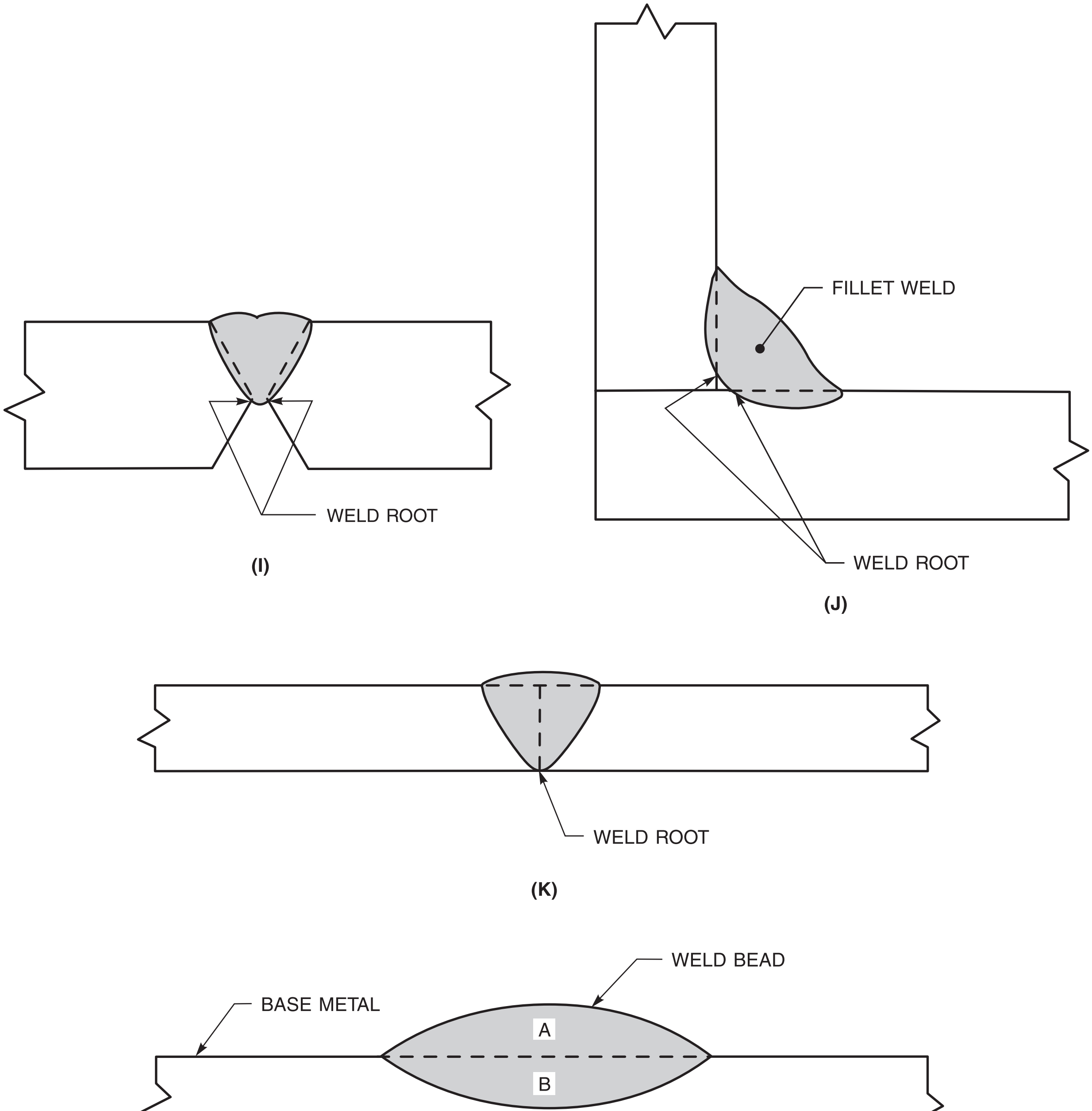


Figure A.13 (Continued)—Parts of a Weld

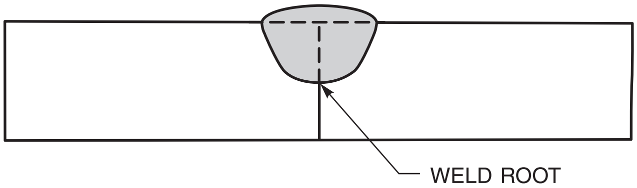


CALCULATION OF BASE METAL DILUTION FROM CROSS-SECTIONAL AREA OF WELD BEAD

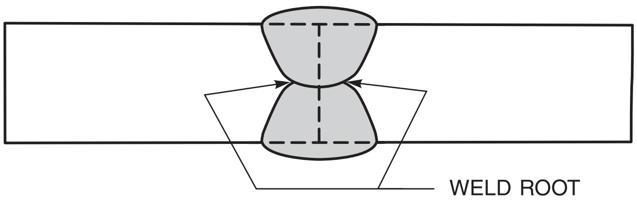
$$\%\ \text{DILUTION} = \frac{B}{A + B} \times 100$$

(L)

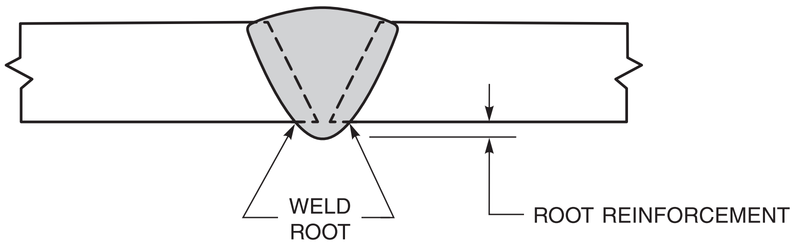
Figure A.13 (Continued)—Parts of a Weld



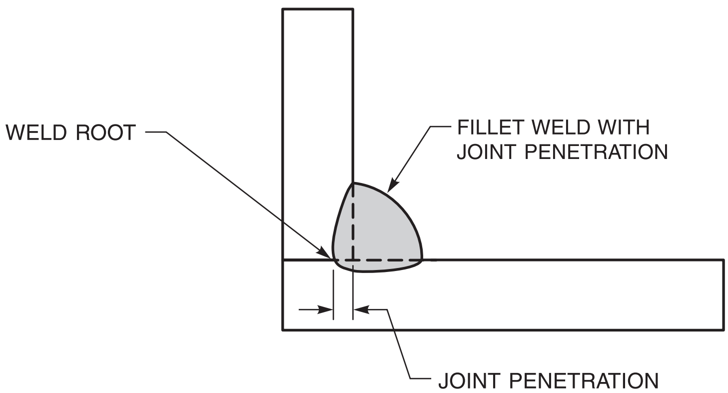
(M) SINGLE-SQUARE-GROOVE WELD



(N) DOUBLE-SQUARE-GROOVE WELD



(O) SINGLE-GROOVE WELD WITH ROOT REINFORCEMENT



(P) FILLET WELD WITH JOINT PENETRATION

Figure A.13 (Continued)—Parts of a Weld

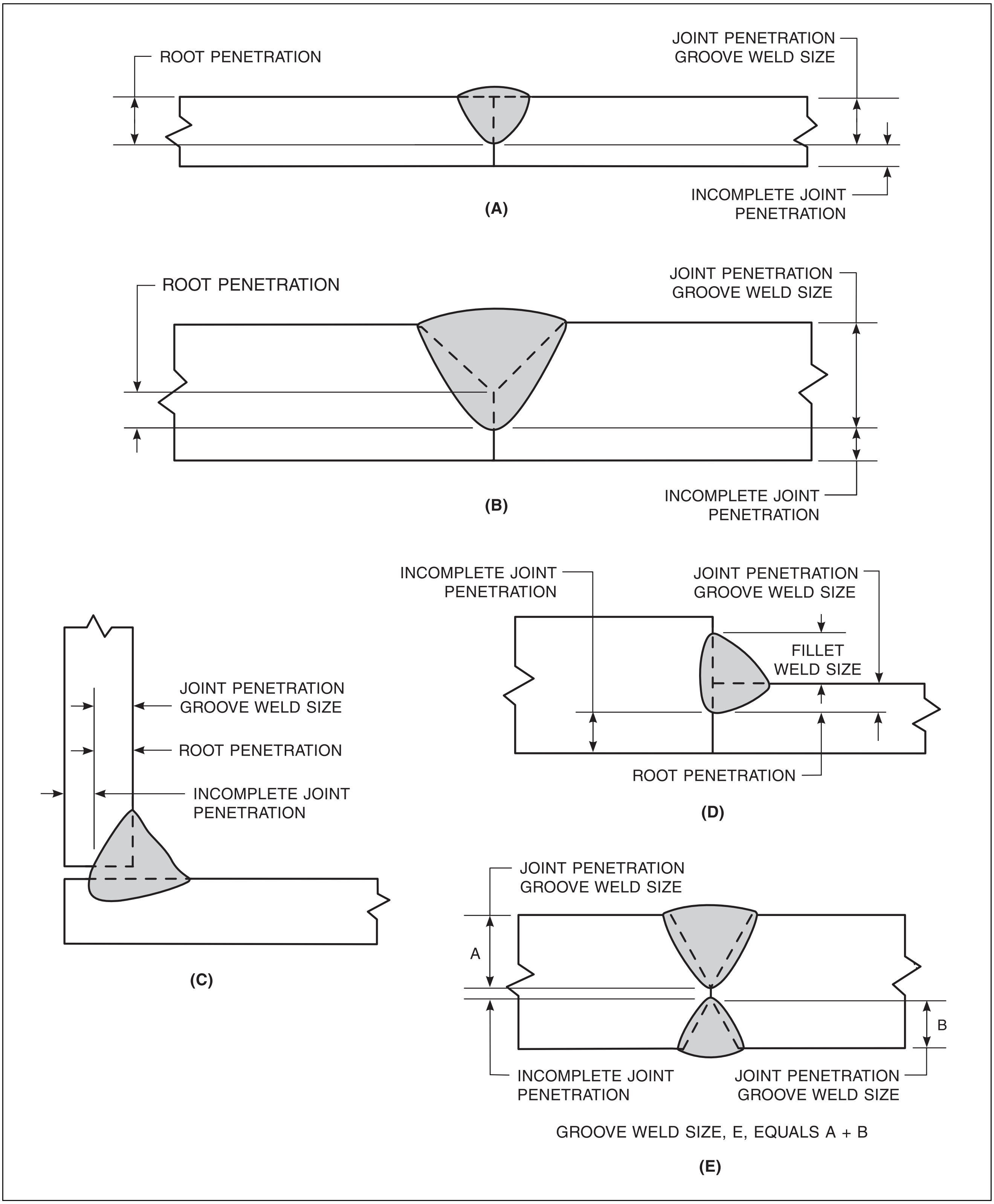


Figure A.14—Groove Weld Size and Joint Penetration

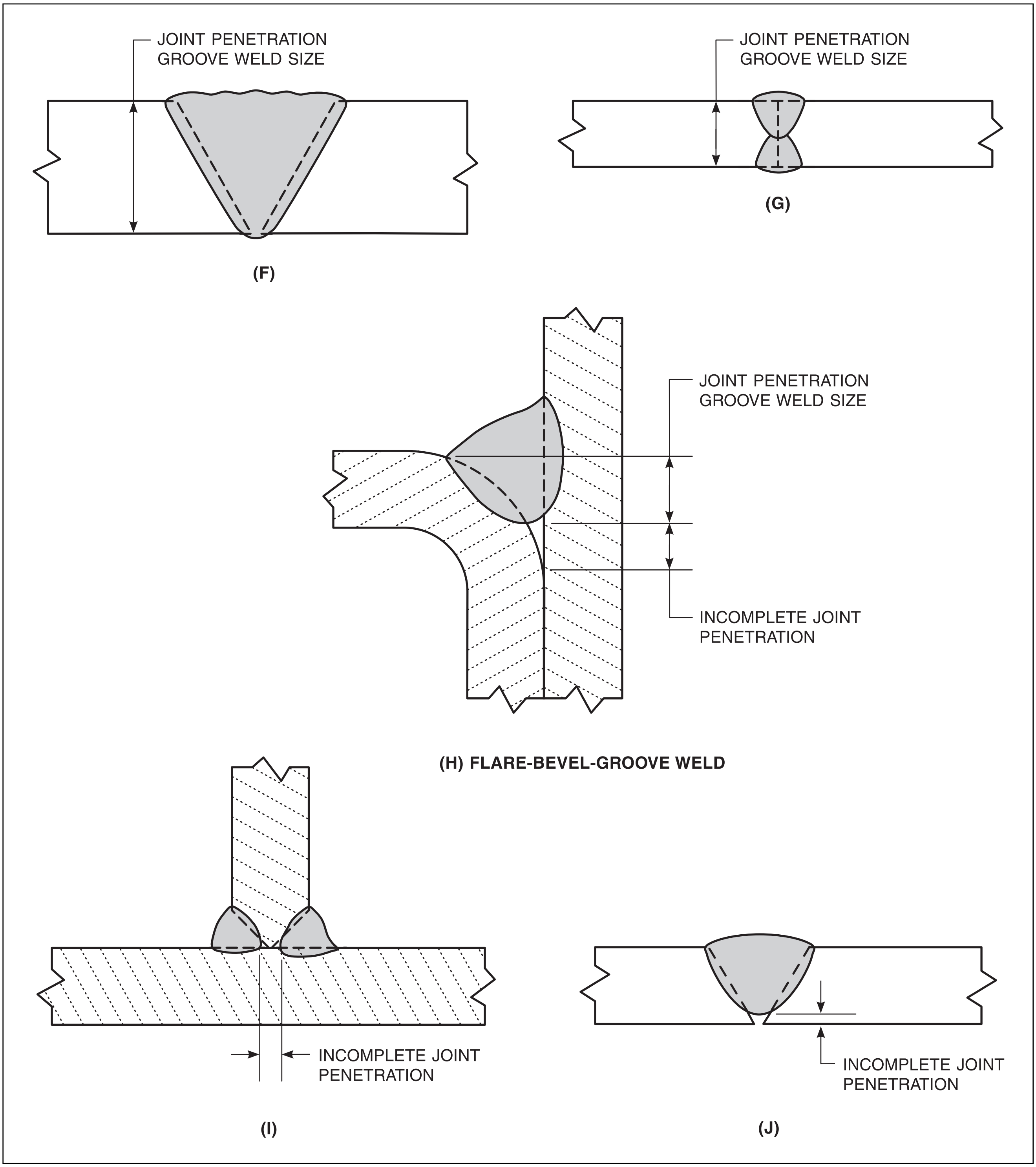


Figure A.14 (Continued)—Groove Weld Size and Joint Penetration

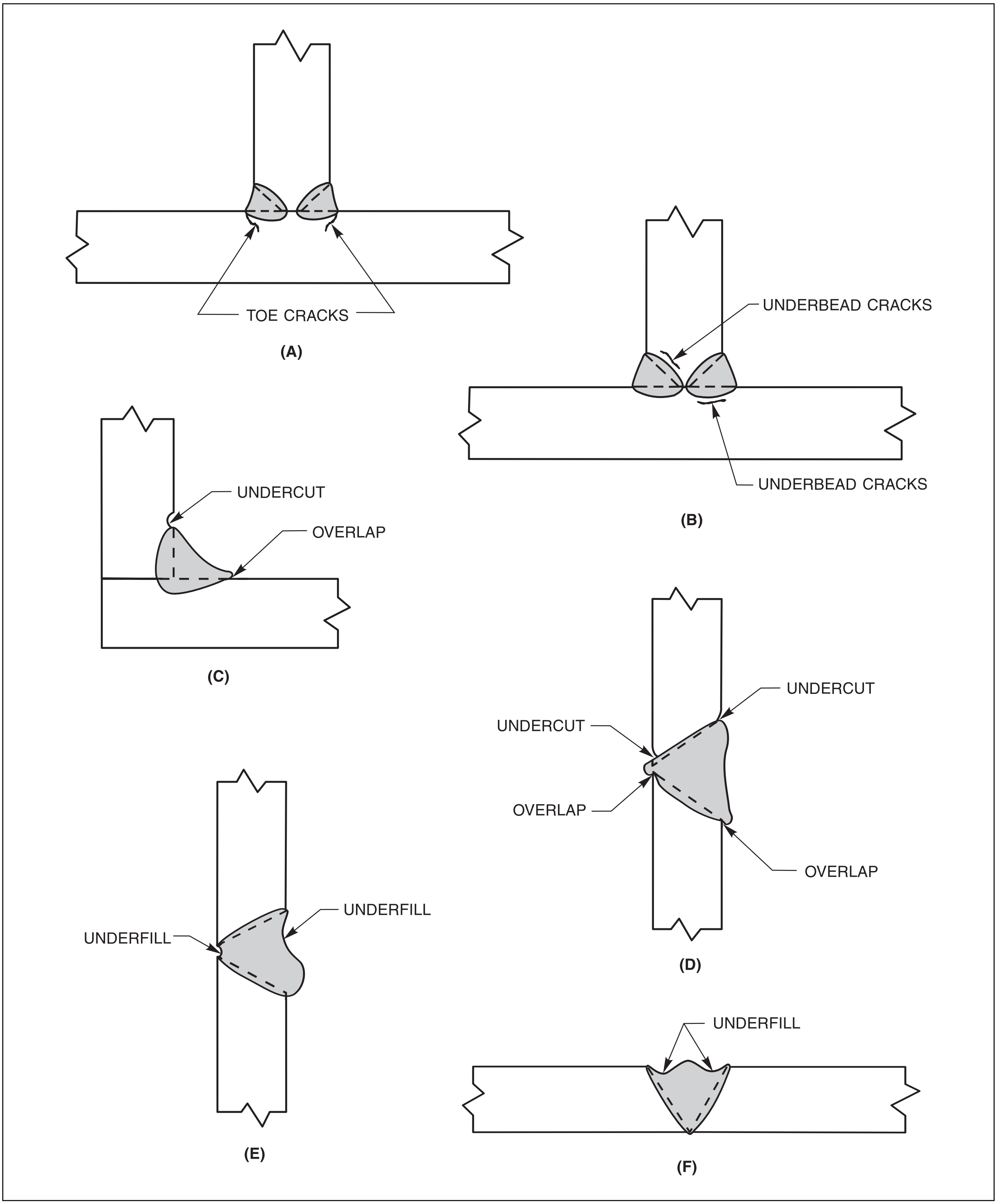


Figure A.15—Weld Discontinuities

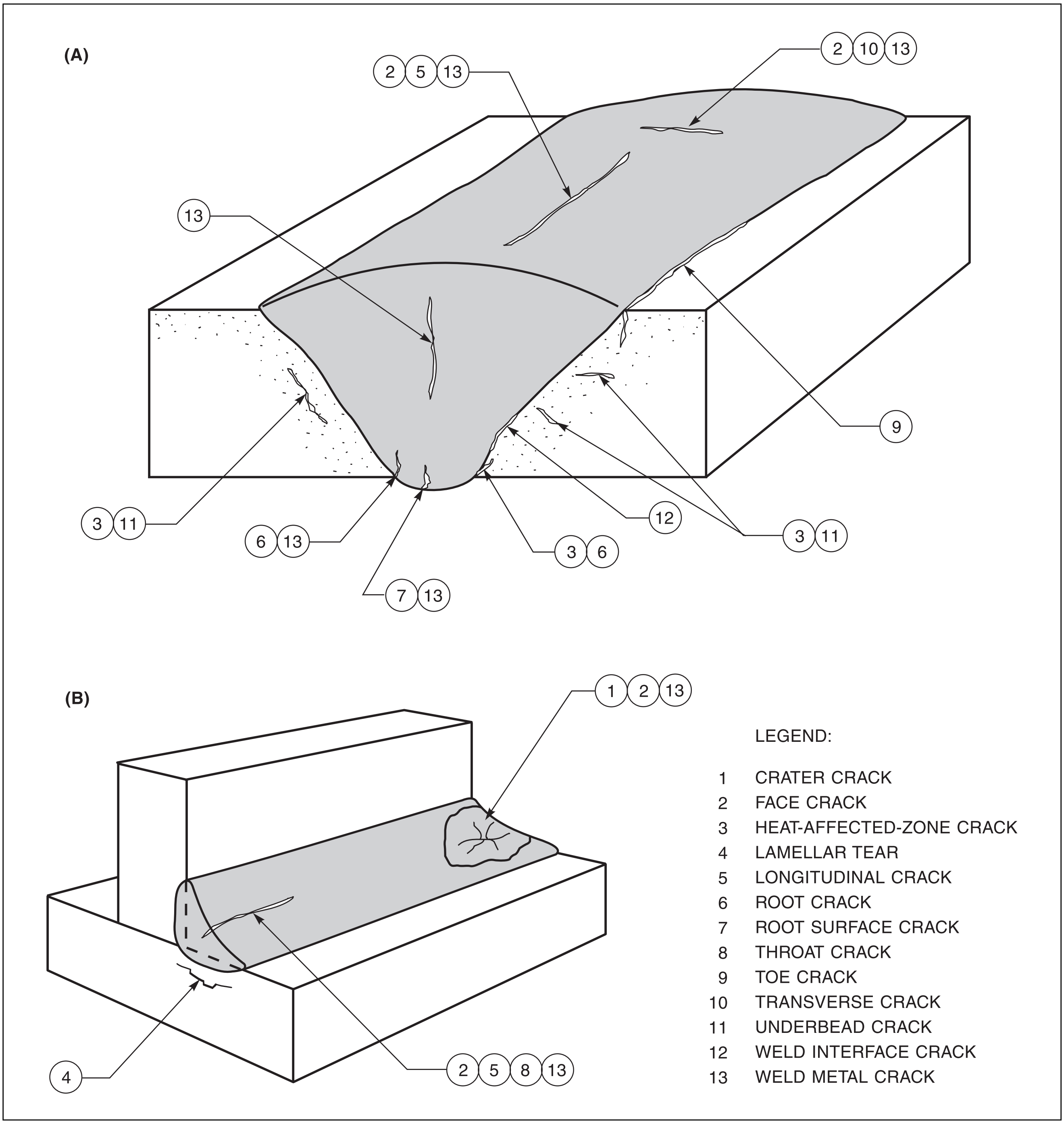


Figure A.16—Crack Types

WELDING AND JOINING PROCESSES

ARC WELDING (AW)

arc stud welding	SW
atomic hydrogen welding	AHW
bare metal arc welding	BMAW
carbon arc welding	CAW
gas carbon arc welding	CAW-G
shielded carbon arc welding	CAW-S
twin carbon arc welding	CAW-T
electrogas welding	EGW
flux cored arc welding	FCAW
gas-shielded flux cored arc welding	FCAW-G
self-shielded flux cored arc welding	FCAW-S
gas metal arc welding	GMAW
pulsed gas metal arc welding	GMAW-P
short circuit gas metal arc welding	GMAW-S
gas tungsten arc welding	GTAW
pulsed gas tungsten arc welding	GTAW-P
magnetically impelled arc welding	MIAW
plasma arc welding	PAW
shielded metal arc welding	SMAW
submerged arc welding	SAW
series submerged arc welding	SAW-S

RESISTANCE WELDING (RW)

flash welding	FW
pressure-controlled resistance welding	RW-PC
projection welding	PW
resistance seam welding	RSEW
high-frequency seam welding	RSEW-HF
induction seam welding	RSEW-I
mash seam welding	RSEW-MS
resistance spot welding	RSW
upset welding	UW
high-frequency	UW-HF
induction	UW-I

SOLDERING (S)

dip soldering	DS
furnace soldering	FS
induction soldering	IS
infrared soldering	IRS
iron soldering	INS
resistance soldering	RS
torch soldering	TS
ultrasonic soldering	USS
wave soldering	WS

SOLID STATE WELDING (SSW)

coextrusion welding	CEW
cold welding	CW
diffusion welding	DFW
hot isostatic pressure welding	HIPW
explosion welding	EXW
forge welding	FOW
friction welding	FRW
direct drive friction welding	FRW-DD
friction stir welding	FSW
inertia friction welding	FRW-I
hot pressure welding	HPW
roll welding	ROW
ultrasonic welding	USW

OXYFUEL GAS WELDING (OFW)

air acetylene welding	AAW
oxyacetylene welding	OAW
oxyhydrogen welding	OHW
pressure gas welding	PGW

BRAZING (B)

block brazing	BB
diffusion brazing	DFB
dip brazing	DB
exothermic brazing	EXB
furnace brazing	FB
induction brazing	IB
infrared brazing	IRB
resistance brazing	RB
torch brazing	TB
twin carbon arc brazing	TCAB

OTHER WELDING AND JOINING

adhesive bonding	AB
braze welding	BW
arc braze welding	ABW
carbon arc braze welding	CABW
electron beam braze welding	EBBW
exothermic braze welding	EXBW
flow brazing	FLB
flow welding	FLOW
laser beam braze welding	LBBW
electron beam welding	EBW
high vacuum	EBW-HV
medium vacuum	EBW-MV
nonvacuum	EBW-NW
electroslag welding	ESW
consumable guide electroslag welding	ESW-CG
induction welding	IW
laser beam welding	LBW
percussion welding	PEW
thermite welding	TW

Figure A.17—Master Chart of Welding and Joining Processes

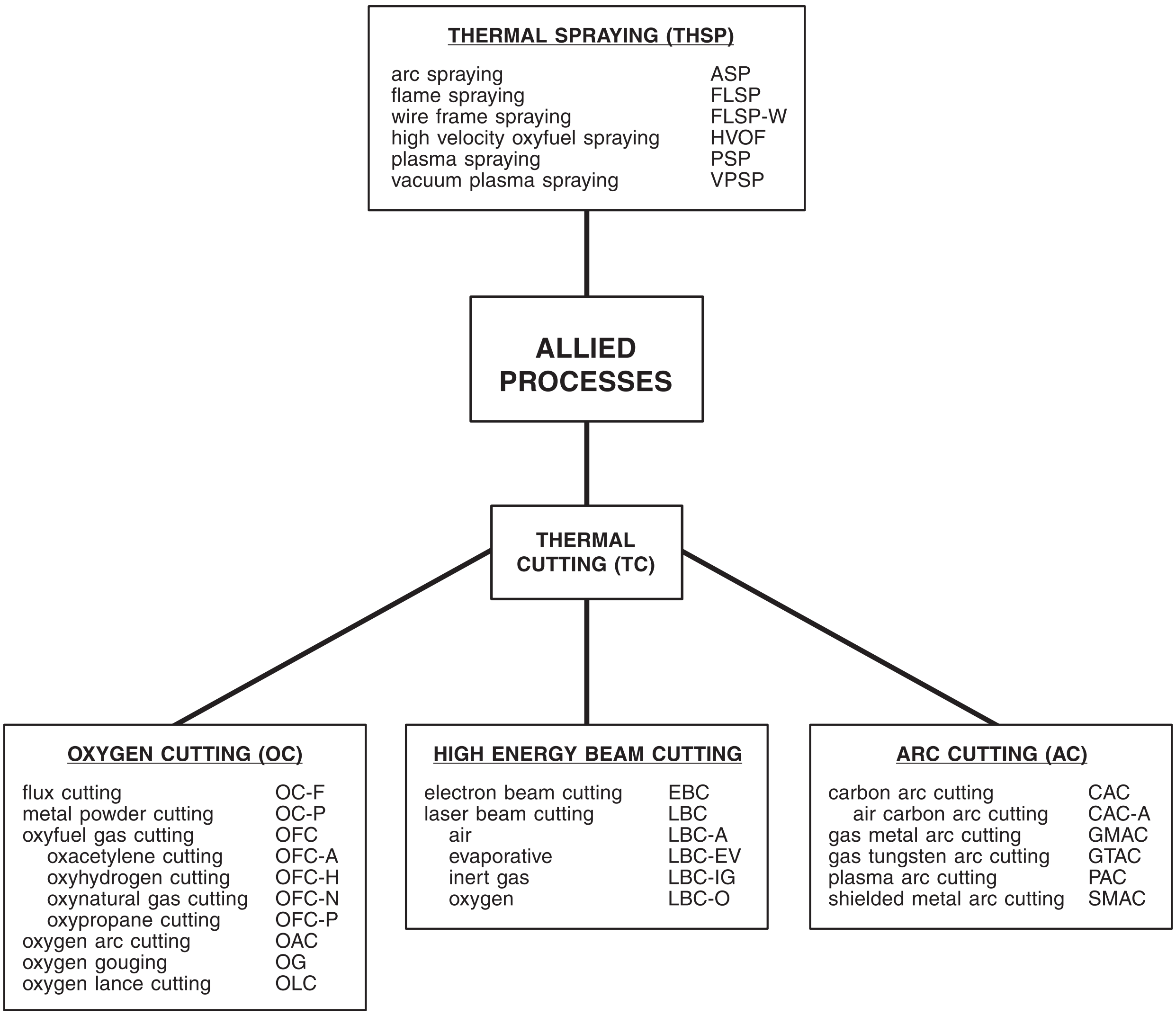


Figure A.18—Master Chart of Allied Processes

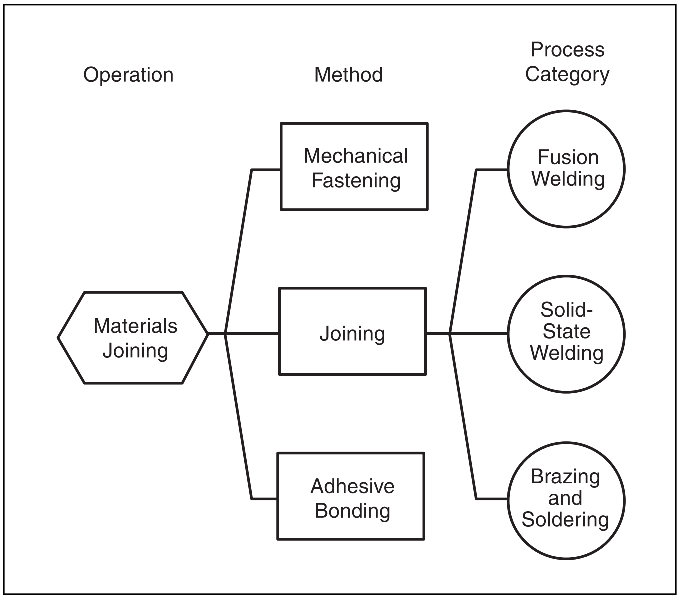
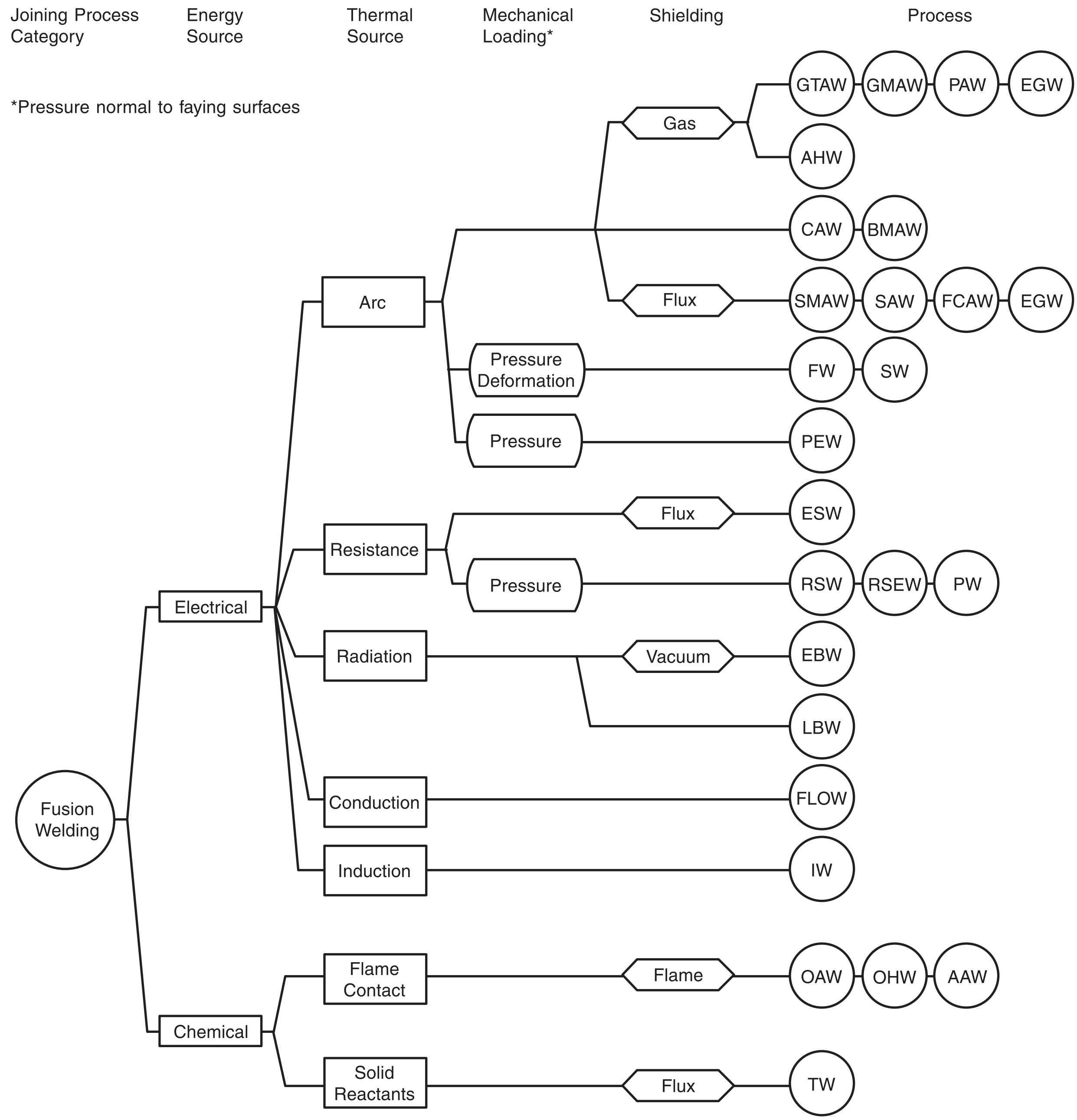


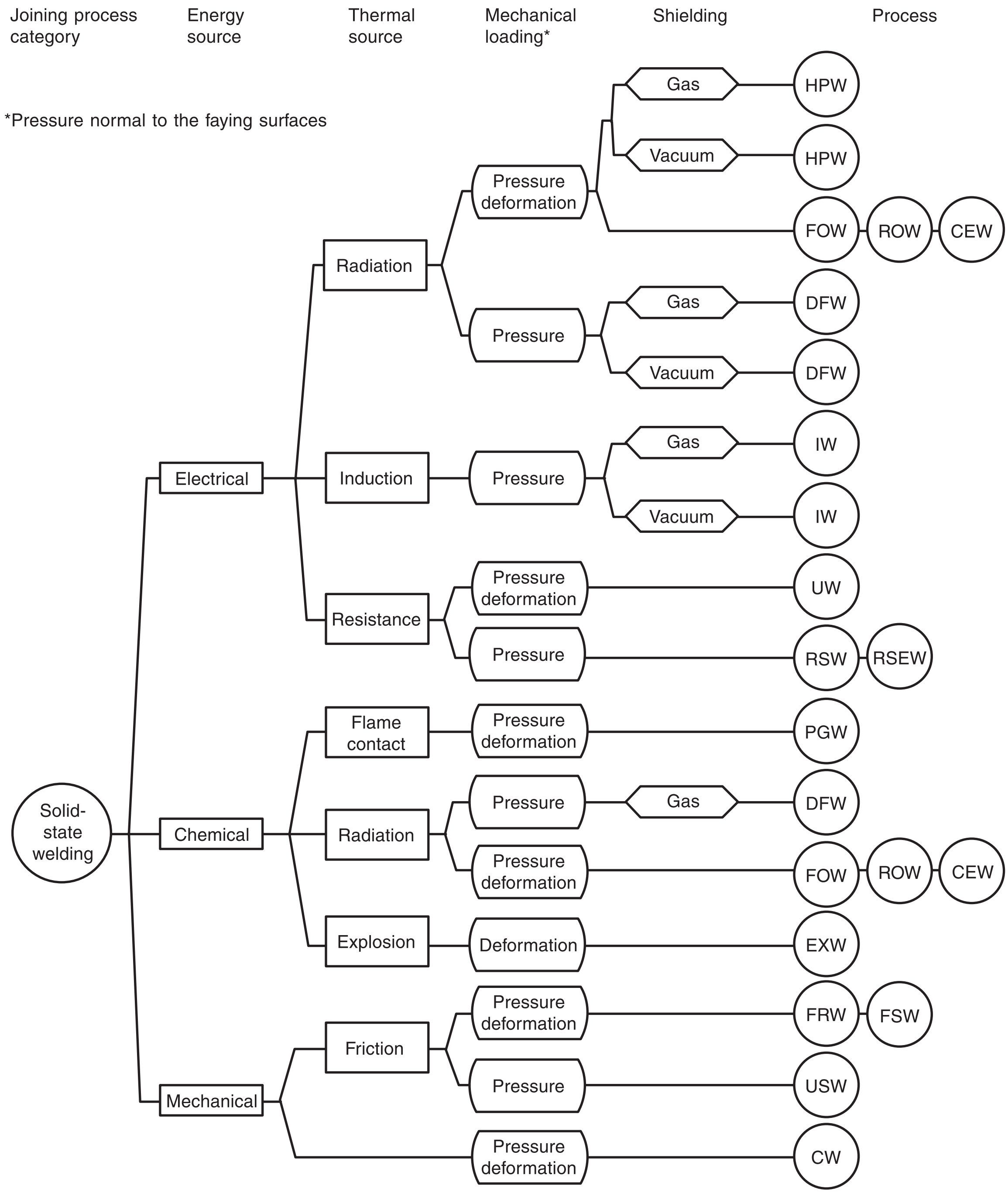
Figure A.19—Joining Method Chart



DEFINITIONS

Designation	Welding Process	Designation	Welding Process	Designation	Welding Process
AAW	air acetylene	FW	flash	PW	projection
AHW	atomic hydrogen	GMAW	gas metal arc	RSEW	resistance seam
BMAW	bare metal arc	GTAW	gas tungsten arc	RSW	resistance spot
CAW	carbon arc	IW	induction	SAW	submerged arc
EBW	electron beam	LBW	laser beam	SMAW	shielded metal arc
EGW	electrogas	OAW	oxyacetylene	SW	stud arc
ESW	electroslag	OHW	oxyhydrogen	TW	thermite
FLOW	flow	PAW	plasma arc		
FCAW	flux cored arc	PEW	percussion		

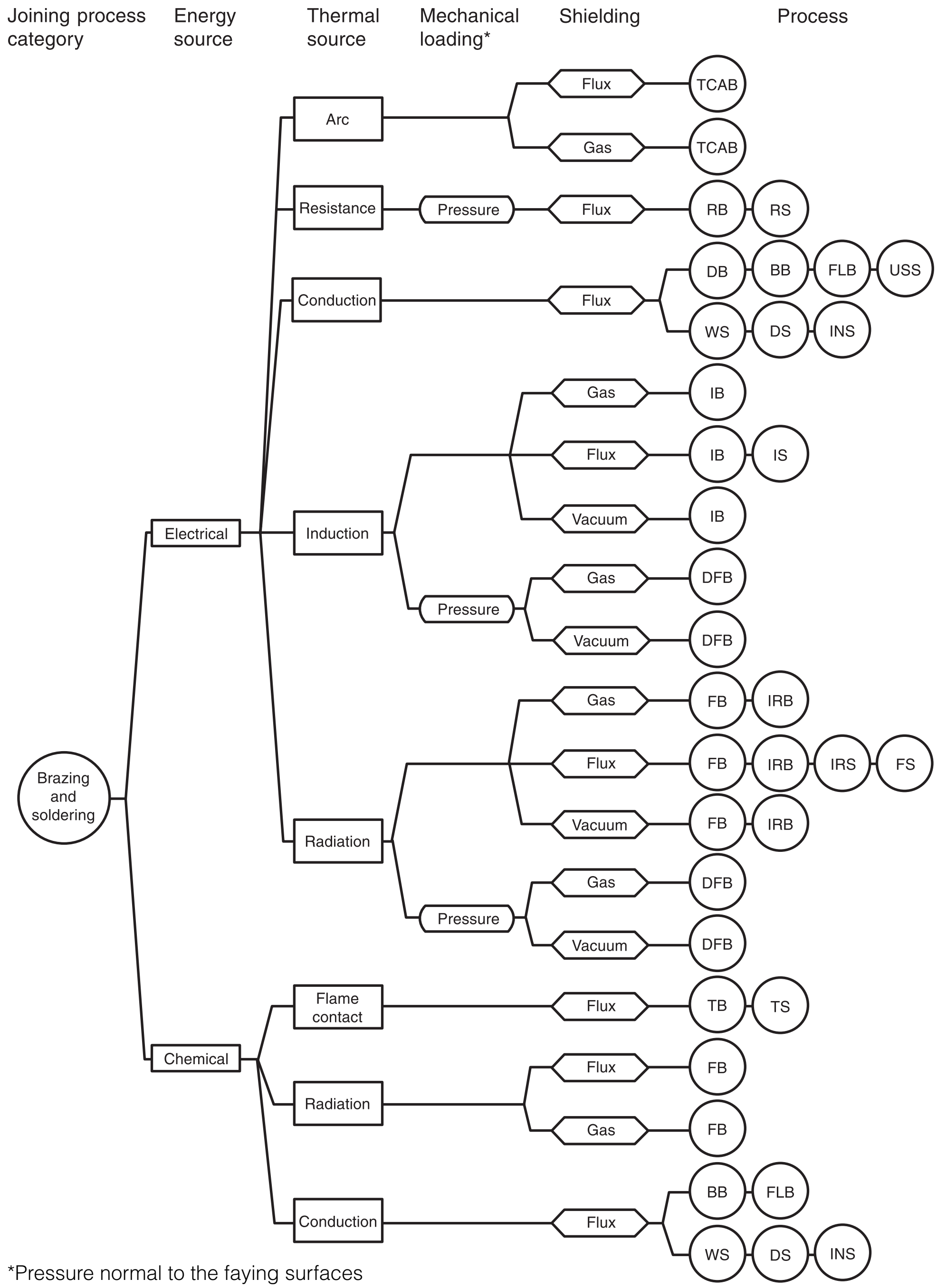
Figure A.20—Fusion Welding Classification



DEFINITIONS

Designation	Welding Process	Designation	Welding Process	Designation	Welding Process
CEW	coextrusion	FRW	friction	RSEW	resistance seam
CW	cold	FSW	friction stir	RSW	resistance spot
DFW	diffusion	HPW	hot pressure	ROW	roll
EXW	explosion	IW	induction	USW	ultrasonic
FOW	forge	PGW	pressure gas	UW	upset

Figure A.21—Solid-State Welding Classification Chart



*Pressure normal to the faying surfaces

DEFINITIONS

Designation	Welding Process	Designation	Welding Process	Designation	Welding Process
AB	arc brazing	FS	furnace soldering	RB	resistance brazing
BB	block brazing	FLB	flow brazing	RS	resistance soldering
TCAB	twin carbon arc brazing	IB	induction brazing	TB	torch brazing
DB	dip brazing	IS	induction soldering	TS	torch soldering
DS	dip soldering	IRB	infrared brazing	USS	ultrasonic soldering
DFB	diffusion brazing	IRS	infrared soldering	WS	wave soldering
FB	furnace brazing	INS	iron soldering		

Figure A.22—Brazing and Soldering Classification Chart

TABLES

Table A1
Letter Designations of Welding and Allied Processes and their Variations

Processes	Letter Designations
adhesive bonding	AB
arc welding	AW
arc stud welding	SW
atomic hydrogen welding	AHW
bare metal arc welding	BMAW
carbon arc welding	CAW
gas carbon arc welding	CAW-G
shielded carbon arc welding	CAW-S
twin carbon arc welding	CAW-T
electrogas welding	EGW
flux cored arc welding	FCAW
gas shielded flux cored arc welding	FCAW-G
self shielded flux cored arc welding	FCAW-S
gas metal arc welding	GMAW
pulsed gas metal arc welding	GMAW-P
short circuit gas metal arc welding	GMAW-S
gas tungsten arc welding	GTAW
pulsed gas tungsten arc welding	GTAW-P
magnetically impelled arc welding	MIAW
plasma arc welding	PAW
shielded metal arc welding	SMAW
submerged arc welding	SAW
series submerged arc welding	SAW-S
brazing	B
block brazing	BB
diffusion brazing	DFB
dip brazing	DB
exothermic brazing	EXB
furnace brazing	FB
induction brazing	IB
infrared brazing	IRB
resistance brazing	RB
torch brazing	TB
twin carbon arc brazing	TCAB
braze welding	BW
arc braze welding	ABW
carbon arc braze welding	CABW
electron beam braze welding	EBBW
exothermic braze welding	EXBW
flow brazing	FLB
flow welding	FLOW
laser beam braze welding	LBW
consumable guide electroslag welding	ESW-CG
electron beam welding	EBW
high vacuum electron beam welding	EBW-HV
medium vacuum electron beam welding	EBW-MV
nonvacuum electron beam welding	EBW-NV
electroslag welding	ESW
induction welding	IW
laser beam welding	LBW
oxyfuel gas welding	OFW
air acetylene welding	AAW
oxyacetylene welding	OAW
oxyhydrogen welding	OHW
pressure gas welding	PGW
percussion welding	PEW
resistance welding	RW
flash welding	FW
pressure-controlled resistance welding	RW-PC
projection welding	PW
resistance seam welding	RSEW
high-frequency seam welding	RSEW-HF
induction seam welding	RSEW-I
mash seam welding	RSEW-MS
resistance spot welding	RSW
upset welding	UW

(Continued)

Table A1 (Continued)
Letter Designations of Welding and Allied Processes and their Variations

Processes	Letter Designations
high-frequency upset welding	UW-HF
induction upset welding	UW-I
soldering	S
dip soldering	DS
furnace soldering	FS
induction soldering	IS
infrared soldering	IRS
iron soldering	INS
resistance soldering	RS
torch soldering	TS
ultrasonic soldering	USS
wave soldering	WS
solid-state welding	SSW
coextrusion welding	CEW
cold welding	CW
diffusion welding	DFW
hot isostatic pressure welding	HIPW
explosion welding	EXW
forge welding	FOW
friction welding	FRW
direct drive friction welding	FRW-DD
friction stir welding	FSW
inertia friction welding	FRW-I
hot pressure welding	HPW
roll welding	ROW
ultrasonic welding	USW
thermal cutting	TC
arc cutting	AC
carbon arc cutting	CAC
air carbon arc cutting	CAC-A
gas metal arc cutting	GMAC
gas tungsten arc cutting	GTAC
plasma arc cutting	PAC
shielded metal arc cutting	SMAC
high energy beam cutting	HEBC
electron beam cutting	EBC
laser beam cutting	LBC
laser beam air cutting	LBC-A
laser beam evaporative cutting	LBC-EV
laser beam inert gas cutting	LBC-IG
laser beam oxygen cutting	LBC-O
oxygen cutting	OC
flux cutting	FOC
metal powder cutting	POC
oxyfuel gas cutting	OFC
oxyacetylene cutting	OFC-A
oxyhydrogen gas cutting	OFC-H
oxynatural gas cutting	OFC-N
oxypropane cutting	OFC-P
oxygen arc cutting	AOC
oxygen gouging	OG
oxygen lance cutting	LOC
thermal spraying	THSP
arc spraying	ASP
flame spraying	FLSP
wire flame spraying	FLSP-W
high velocity oxyfuel spraying	HVOF
plasma spraying	PSP
vacuum plasma spraying	VPSP
thermite welding	TW

Table A2
Alphabetical Cross Reference to Table 1 by Process

Processes and Variations	Letter Designations
adhesive bonding	AB
air acetylene welding	AAW
air carbon arc cutting	CAC-A
arc braze welding	ABW
arc cutting	AC
arc spraying	ASP
arc stud welding	SW
arc welding	AW
atomic hydrogen welding	AHW
bare metal arc welding	BMAW
block brazing	BB
braze welding	BW
brazing	B
carbon arc braze welding	CABW
carbon arc cutting	CAC
carbon arc welding	CAW
coextrusion welding	CEW
cold welding	CW
consumable guide electroslag welding	ESW-CG
diffusion brazing	DFB
diffusion welding	DFW
dip brazing	DB
dip soldering	DS
direct drive friction welding	FRW-DD
electrogas welding	EGW
electron beam braze welding	EBBW
electron beam cutting	EBC
electron beam welding	EBW
electroslag welding	ESW
exothermic braze welding	EXBW
exothermic brazing	EXB
explosion welding	EXW
flame spraying	FLSP
flash welding	FW
flow brazing	FLB
flow welding	FLOW
flux cored arc welding	FCAW
flux cutting	FOC
forge welding	FOW
friction stir welding	FSW
friction welding	FRW
furnace brazing	FB
furnace soldering	FS
gas carbon arc welding	CAW-G
gas metal arc cutting	GMAC
gas metal arc welding	GMAW
gas shielded flux cored arc welding	FCAW-G
gas tungsten arc cutting	GTAC
gas tungsten arc welding	GTAW
high energy beam cutting	HEBC
high vacuum electron beam welding	EBW-HV
high velocity oxyfuel spraying	HVOF
high-frequency seam welding	RSEW-HF
high-frequency upset welding	UW-HF
hot isostatic pressure welding	HIPW
hot pressure welding	HPW
induction brazing	IB
induction seam welding	RSEW-I
induction soldering	IS
induction upset welding	UW-I
induction welding	IW
inertia friction welding	FRW-I
infrared brazing	IRB
infrared soldering	IRS
iron soldering	INS
laser beam air cutting	LBC-A

(Continued)

Table A2
Alphabetical Cross Reference to Table 1 by Process

Processes and Variations	Letter Designations
laser beam braze welding	LBBW
laser beam cutting	LBC
laser beam evaporative cutting	LBC-EV
laser beam inert gas cutting	LBC-IG
laser beam oxygen cutting	LBC-O
laser beam welding	LBW
magnetically impelled arc welding	MIAW
mash seam welding	RSEW-MS
medium vacuum electron beam welding	EBW-MV
metal powder cutting	POC
nonvacuum electron beam welding	EBW-NV
oxyacetylene cutting	OFC-A
oxyacetylene welding	OAW
oxyfuel gas cutting	OFC
oxyfuel gas welding	OFW
oxygen arc cutting	AOC
oxygen cutting	OC
oxygen gouging	OG
oxygen lance cutting	LOC
oxyhydrogen gas cutting	OFC-N
oxyhydrogen welding	OHW
oxynatural gas cutting	OFC-N
oxypropane cutting	OFC-P
percussion welding	PEW
plasma arc cutting	PAC
plasma arc welding	PAW
plasma spraying	PSP
pressure gas welding	PGW
pressure-controlled resistance welding	RW-PC
projection welding	PW
pulsed gas metal arc welding	GMAW-P
pulsed gas tungsten arc welding	GTAW-P
resistance brazing	RB
resistance seam welding	RSEW
resistance soldering	RS
resistance spot welding	RSW
resistance welding	RW
roll welding	ROW
self shielded flux cored arc welding	FCAW-S
series submerged arc welding	SAW-S
shielded carbon arc welding	CAW-S
shielded metal arc cutting	SMAC
shielded metal arc welding	SMAW
short circuit gas metal arc welding	GMAW-S
soldering	S
solid-state welding	SSW
submerged arc welding	SAW
thermal cutting	TC
thermal spraying	THSP
thermite welding	TW
torch brazing	TB
torch soldering	TS
twin carbon arc brazing	TCAB
twin carbon arc welding	CAW-T
ultrasonic soldering	USS
ultrasonic welding	USW
upset welding	UW
vacuum plasma spraying	WS
wave soldering	WS
wire flame spraying	FLSP-W

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American Welding Society (AWS) Committee on Definitions and Symbols. 1998. *Standard symbols for welding, brazing, and nondestructive examination*. ANSI/AWS A2.4-98. Miami: American Welding Society.

8. The dates of publication given for the codes and other standards listed here were current at the time this chapter was prepared. The reader is advised to consult the latest edition.

METRIC PRACTICE GUIDE FOR THE WELDING INDUSTRY

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Contents

APPENDIX B

METRIC PRACTICE GUIDE FOR THE WELDING INDUSTRY

INTRODUCTION

The American Welding Society's *Metric Practice Guide for the Welding Industry,* AWS A1.1,[1,2] is based on the Système International d'Unités, or International System of Units (SI), as defined in the U.S. Federal Register notice *Metric System of Measurement: Interpretation of the International System of Units for the United States*, dated July 28, 1998.[3] This standard contains specifications of the SI base units, derived units, prefixes, and rules for their use in American Welding Society (AWS) documents and by the welding industry. It also contains factors and rules for converting from inch-pound units (often referred to as U.S. customary units) to SI units and recommendations to industry for managing the transition to the International System of Units.

The American Welding Society (AWS) Policy on Metrication states, in part, that "AWS supports a timely transition to the use of SI units. The American Welding Society recognizes that the inch-pound system of units will eventually be replaced by the SI units. To delay the transition to SI units and to lengthen unnecessarily the transition period result in greater costs and confusion and increases the loss of compatibility with the international market."

At present, the United States stands alone as the only industrial country that still predominantly uses the inch-pound units of measurement. Since the signing of the Metric Act of 1975 by President Gerald Ford and an initial flurry of transition, the voluntary feature of the Act allowed the impetus to stagnate. We now find ourselves at odds not only with other industrial countries, but also, in many cases, with each other.

Many major companies—including General Motors Corporation, Ford Motor Company, DaimlerChrysler Corporation, and an estimated 70% of the Fortune 500—have made the switch in some aspect of their businesses. However, smaller firms, typically those with fewer international interactions, have been slower to change.

More recently, the Omnibus Trade and Competitiveness Act, which was signed by President Ronald Reagan in August 1988, designated the SI version of the metric system of units as preferred for U.S. trade and commerce. Specifically, this act requires each federal agency to use SI in its procurements, grants, and other business-related activities.

In 1973, the Metric Practice Subcommittee was formed under the AWS Committee on Definitions, Symbols, and Metric Practice to provide guidance to the welding industry on the use of and conversion to SI units. The continued interest in metric practice within

1. American Welding Society Committee on Metric Practice, *Metric Practice Guide for the Welding Industry,* AWS A1.1, Miami: American Welding Society.
2. At the time of the preparation of this chapter, 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 document referred to 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 or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.
3. National Institute of Standards and Technology (NIST), *Metric System of Measurement: Interpretation of the International System of Units for the United States,* Notice: Tuesday, July 28, 1998, *Federal Register* Volume 63, Number 144, Washington, D.C.: Government Printing Office.

the American Welding Society resulted in the reorganization of the former Metric Practice Subcommittee into the present AWS A1 Committee on Metric Practice.

Because a comprehensive document relating specifically to welding nomenclature was not available, the first task of the subcommittee was to prepare a metric practice guide. The first edition was issued in 1975. Improvements suggested by readers and users resulted in revisions in 1980, 1989, and 1998. The fifth edition reflects the state of the art in metric practice for the U.S. welding industry. It aims to assist the welding industry in converting to the International System of Units and promote this system's voluntary use.[4]

INTERNATIONAL SYSTEM OF UNITS (SI)

A system of units is any collection of related units. The International System of Units (SI) has evolved from older metric systems. Adopted by the highest international authority on units, Conférence Générale des Poids et Mesures [General Conference on Weights and Measures], SI is suitable for customary, technical, and scientific use. It is the only system of units of measure that has the properties outlined below:

1. Completeness, which requires that a unit of measurement be defined for every quantity of interest in the physical sciences and technologies;
2. Coherence, which requires that all derived units in the system be obtained from the base units by the rules of multiplication and division with no numerical factor other than the number one (1) ever occurring in the expressions for derived units in terms of the base units. The system of units must also be coherent with its corresponding system of quantities and equations. A system of units is coherent with respect to a system of quantities and equations if the system of units is chosen in such a way that the equations between numerical values have exactly the same form (including numerical factors) as the corresponding equations between quantities; and
3. Uniqueness, which requires that there be one and only one unit defined for each quantity. For example, the SI units for force (newton), energy (joule), and power (watt) are the same, respectively, whether the process is mechanical, electrical, or thermal.

4. This appendix is adapted from AWS Committee on Metric Practice, 200X, *Metric Practice Guide for the Welding Industry,* AWS A1.1:200X, Miami: American Welding Society.

ADVANTAGES

The International System of Units (SI) is the metric system of units in its latest form. SI is the only system of units which fully satisfies all the above three requirements for completeness, coherence, and uniqueness. Within SI, a set of base-ten prefixes is defined to form decimal multiples and submultiples of SI units. SI units and their base-ten multiples and submultiples are in harmony with the decimal system of arithmetic, facilitating easy numerical calculations. Awkward manipulations of common fractions such as 1/16, 1/32, and 1/64 are unnecessary.

All industrial nations, including the United States, by the Omnibus Trade and Competitiveness Act of 1988 (Public Law 100-418) have chosen the International System of Units as the preferred system of units for all applications in science, engineering, technology, commerce, and trade.

SI UNITS AND SYMBOLS

The International System of Units (SI) consists of seven base units, derived units, and a set of prefixes for the formation of multiples of the various units.

SI BASE UNITS

The SI base quantities and the names of the corresponding SI base units, their symbols, and definitions are presented in Table B.1.

SI DERIVED UNITS

Some SI derived units are formed as described and have been given special names and symbols. Examples are listed in Table B.2.

PREFIXES

SI prefixes may be used to indicate multiples of SI units, thus simplifying numeric terms and providing a convenient substitute for writing powers of ten as generally preferred in computation. For example, 16 800 meters or 16.8×10^3 meters becomes 16.8 kilometers. In this case, the appropriate prefix is attached to the base –*gram*. Table B.3 presents the list of prefixes, and examples of their use are provided below. It should be noted that the kilogram is the only SI base or derived unit whose name, for historical reasons, contains a prefix.

Table B.1
SI Base Units

Base Quantity	Unit Name	Unit Symbol	Definition
length	meter	m	The length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second.
mass	kilogram	kg	The mass equal to the mass of the international prototype of the kilogram.
time	second	s	The duration equal to 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
electrical current	ampere	A	That constant current which, if maintained in two straight parallel conductors of infinite length and of negligible circular cross section and placed one meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.
thermodynamic temperature	kelvin	K	The thermodynamic temperature that is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
luminous intensity	candela	cd	The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.
amount of substance	mole	mol	The amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilograms of carbon-12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

Table B.2
Examples of SI Derived Units

Derived Quantity	Unit Name	Unit Symbol	Expression in Terms of Other SI Units	Expression in Terms of SI Base Units
acceleration	meter per second squared			$m \cdot s^{-2}$
amount-of-substance concentration (concentration)	mole per cubic meter			$mol \cdot m^{-3}$
angular acceleration	radian per second squared		rad/s^2	$m \cdot m^{-1} \cdot s^{-2} = s^{-2}$
angular velocity	radian per second		rad/s	$m \cdot m^{-1} \cdot s^{-1} = s^{-1}$
area	square meter			m^2
capacitance	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
Celsius temperature	degree Celsius	°C		K
current density	ampere per square meter			$A \cdot m^{-2}$
dynamic viscosity	pascal second		$Pa \cdot s$	$m^{-1} \cdot kg \cdot s^{-1}$
electric charge density	coulomb per cubic meter		C/m^3	$m^{-3} \cdot s \cdot A$
electric charge, quantity of electricity	coulomb	C		$s \cdot A$
electric conductance	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
electric field strength	volt per meter		V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
electric flux density	coulomb per square meter		C/m^2	$m^{-2} \cdot s \cdot A$
electric potential difference, electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
electric resistance	ohm	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
energy density	joule per cubic meter		J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
exposure (X- and γ-rays)	coulomb per kilogram		C/kg	$kg^{-1} \cdot s \cdot A$
force	newton	N		$m \cdot kg \cdot s^{-2}$

(Continued)

Table B.2 (Continued)
Examples of SI Derived Units

Derived Quantity	Unit Name	Unit Symbol	Expression in Terms of Other SI Units	Expression in Terms of SI Base Units
frequency	hertz	Hz		s^{-1}
heat capacity, entropy	joule per kelvin		J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
heat flux density, irradiance	watt per square meter		W/m^2	$kg \cdot s^{-3}$
illuminance	lux	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd = m^{-2} \cdot cd$
inductance	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
luminance	candela per square meter			$cd \cdot m^{-2}$
luminous flux	lumen	lm	$cd \cdot sr$	$m^2 \cdot m^{-2} \cdot cd = cd$
magnetic field strength	ampere per meter			$A \cdot m^{-1}$
magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
mass density (density)	kilogram per cubic meter			$kg \cdot m^{-3}$
mass fraction	kilogram per kilogram, which may be represented by the number 1			$kg \cdot kg^{-1} = 1$
molar energy	joule per mole		J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
molar entropy, molar heat capacity	joule per mole kelvin		$J/(mol \cdot K)$	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
moment of force	newton meter		$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
permeability	henry per meter		H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
permittivity	farad per meter		F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
plane angle	radian	rad		$m \cdot m^{-1} = 1$
power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
solid angle	steradian	sr		$m^2 \cdot m^{-2} = 1$
specific energy	joule per kilogram		J/kg	$m^2 \cdot s^{-2}$
specific heat capacity, specific entropy	joule per kilogram kelvin		$J/(kg \cdot K)$	$m^2 \cdot s^{-2} \cdot K^{-1}$
specific volume	cubic meter per kilogram			$m^3 \cdot kg^{-1}$
speed, velocity	meter per second			$m \cdot s^{-1}$
surface tension	newton per meter		N/m	$kg \cdot s^{-2}$
thermal conductivity	watt per meter kelvin		$W/(m \cdot K)$	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
volume	cubic meter			m^3
wave number	reciprocal meter			m^{-1}

Table B.3
SI Prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^9	giga	G	10^{-12}	pico	p
10^6	mega	M	10^{-15}	femto	f
10^3	kilo	k	10^{-18}	atto	a
10^2	hecto	h	10^{-21}	zepto	z
10^1	deka	da	10^{-24}	yocto	y

OTHER UNITS USED WITH SI

Certain units, although not part of SI, are in widespread use and are acceptable for use with SI. Table B.4 presents examples of these.

Table B.4
Other Units That May be Used with SI Units

Units	Symbol	Value
minute	min	1 min = 60 s
hour	h	1 h = 60 min = 3600 s
day	d	1 d = 24 h = 1440 min = 86 400 s
degree (angular)	°	1° = (π/180) rad = 0.0175 rad
liter	L	1 L = 0.001 m^3 = 1 dm^3
metric ton	t	1 t = 1000 kg

UNITS PERTAINING TO WELDING

Table B.5 lists the recommended SI multiples to be used in welding nomenclature. The selection of these terms was based on use of (1) SI units where practicable, (2) numbers of reasonable size, and (3) accepted units currently in use.

Filler metal and fillet sizes are tabulated in Tables B.6 and B.7. SI values are approximate equivalents for conversion on drawings, specifications, and so forth. These values are for conversion only and are not intended for new designs where a more rational series for sizing, such as that shown in the column labeled "Rational Series" in Table B.7, may be used.

Table B.5
Units Pertaining to Welding

Quantity	SI Units or Multiples	Symbol
area dimensions	square millimeter	mm^2
current density	ampere per square millimeter	A/mm^2
deposition rate	kilogram per hour	kg/h
electrical resistivity	ohm meter	$\Omega \cdot m$
electrode force	newton	N
flow rate (gas and liquid)	liter per minute	L/min
fracture toughness	meganewton meter$^{-3/2}$	$MN \cdot m^{-3/2}$
impact energy absorption	joule	$J = N \cdot m$
linear dimensions	millimeter	mm
moment of force (torque)	newton meter	$N \cdot m$
power density	watt per square meter	W/m^2
pressure (gas and liquid)	kilopascal	kPa = 1000 N/m^2
pressure (vacuum)	pascal	Pa = N/m^2
tensile strength	megapascal	MPa = 1 000 000 N/m^2
thermal conductivity	watt per meter kelvin	$W/(m \cdot K)$
travel speed	millimeter per second	mm/s
volume dimensions	cubic millimeter	mm^3
wire feed speed	millimeter per second	mm/s

Table B.6
Filler Metal Sizes

Fractional in.	Decimal Equivalents, in.	Standard ISO 544*, mm
	0.020	**0.5**
	0.024	**0.6**
	0.025	
	0.030	
	0.031	**0.8**
	0.035	**0.9**
	0.039	**1.0**
	0.045	
3/64	0.047	1.2
	0.052	
	0.055	1.4
	0.060	
1/16	0.062	1.6
	0.068	1.7
	0.071	1.8
5/64	0.078	2.0
3/32	0.094	2.4
	0.098	2.5
	0.110	2.8
	0.118	3.0
	0.120	
1/8	0.125	3.2
5/32	0.156	4.0
3/16	0.188	
	0.197	5.0
7/32	0.219	
	0.236	6.0
1/4	0.250	
5/16	0.313	8.0

*International Organization for Standardization (ISO), Forthcoming, *Technical Delivery Conditions for Welding Filler Materials—Type of Product, Dimensions, Tolerances, and Marking*, ISO 544, Geneva: International Organization for Standardization. **Bolded** items are available in bare wire only.

Table B.7
Fillet Sizes

Approximate Equivalents in.	Approximate Equivalents mm	Rational Series mm
1/8	3	3
5/32	4	4
3/16	5	5
1/4	6	6
5/16	8	8
3/8	10	10
7/16	11	12
1/2	13	—*
5/8	16	16
3/4	19	20
1	25	25

*No value is required in this interval for rational sizing. See the Preferred Number 10 Series in Table B.12 and the example given in the section "Application of Preferred Numbers."

USAGE

The SI units used for mass, force, weight, temperature, time, angles, stress, and pressure are discussed in this section.

MASS, FORCE, AND WEIGHT

In SI, the unit of mass is the kilogram (kg), and the unit of force is the newton (N). In everyday use, and especially in common parlance, the term *weight* is often used as a synonym for *mass*. As a measure of mass, the term *weight* should be restricted to commercial usage. Examples of correct and incorrect usages are given below:

Correct	Incorrect
N/m^2	kgf/m^2

TEMPERATURE

The SI unit for thermodynamic temperature is the kelvin. The SI unit for Celsius temperature, used in most common applications, is the degree Celsius. The degree Celsius was formerly called the "degree centigrade." The degree Fahrenheit should not be used.

TIME

The SI unit for time is the second. The use of the minute (min), the hour (h), and the day (d), which are non-SI units, is permissible.

ANGLES

The SI unit for plane angle is the radian. The SI unit for solid angle is the steradian. The degree symbol (°) may be used where appropriate or convenient, and the value should be decimalized. Angular minutes and seconds should be avoided, as indicated below:

Preferred	Nonpreferred
5.8°	5°8'32"

STRESS AND PRESSURE

The SI unit for pressure and stress is the *pascal*, which is the special name given to the newton per square meter. The unit *kilopascal* is appropriate for most pressures encountered in welding practice, and the unit *megapascal* is appropriate for most stresses. Other units for pressure and stress, such as those shown as incorrect forms below, should not be used:

Correct	Incorrect
N/m^2, Pa, kPa, MPa	kgf/cm^2, psi

STYLE

Stylistic conventions with respect to parallelism, the use of prefixes, capitalization, the formation of plurals, writing numbers, the representation of mathematical operations, and punctuation as well as typographical considerations are presented in the section.

PARALLELISM

Only parallel terms—that is, unit names with other unit names or unit symbols with other unit symbols—are used in a single expression. Unit symbols and unit names are never used in combination in the same expression. An example is presented below:

Correct	Incorrect
meter per second, m/s	meter/s

PREFIXES

Prefixes may be used with SI units to indicate multiples. Prefixes provide convenient substitutes for using powers of ten, and they eliminate insignificant digits, as illustrated below:

Preferred	Acceptable
12.3 km	12 300 m, 12.3×10^3 m

Prefixes in steps of 1000 are recommended. It is generally desirable to avoid the prefixes *hecto*, *deka*, *deci*, and *centi* in technical writing for the welding industry. Examples of preferred and nonpreferred forms are provided below:

Preferred	Nonpreferred
mm, m, km	hm, dam, dm, cm

It is generally desirable that the prefix chosen places the numerical value between 0.1 and 1000. However, for special situations such as tabular presentations, this recommendation may be inappropriate. Multiple and hyphenated prefixes must not be used. Examples of correct and incorrect usages are given below:

Correct	Incorrect
pF, Gg, GW	µµF, Mkg, kMW, G-W

It is generally desirable to use only base and derived units in the denominator. Prefixes are used with the numerator unit to give numbers of the appropriate size, as indicated below:

Preferred	Nonpreferred
200 J/kg	0.2 J/g
1 Mg/m	1 kg/mm
1 MPa, 1 MN/m^2	1 N/mm^2

Prefixes should not be mixed unless magnitudes warrant a difference. An example of this convention is presented below:

Preferred	Nonpreferred
5 mm long × 10 mm high	5 mm long × 0.01 m high

Exception
4 mm diameter × 50 m long

CAPITALIZATION

SI unit names (e.g., newton, pascal, meter, kelvin, and hertz) are capitalized only at the beginning of a sentence. One exception is the word *Celsius,* as in "degree Celsius," which is always capitalized.

SI unit symbols are not capitalized except for those derived from a proper name (e.g., A for ampere, J for joule, K for Kelvin, N for newton, P for pascal, and W for watt). Although both lowercase "l" and upper case "L" are internationally accepted symbols for *liter,* to avoid the risk of confusion, the preferred symbol for the use in the United States is "L."

Only seven prefix symbols are capitalized, namely, "Y" for *yotta*; "Z" for *zetta*; "E" for *exa*; "P" for *peta*; "T" for *tera*; "G" for *giga*; and "M" for *mega*.

PLURALS

Unit names form their plurals in the manner customary for the English language. However, unit symbols are invariable in form; that is, they are the same for both singular and plural forms. Examples are presented below:

Correct	Incorrect
50 newtons	50 newton
1 N, 50 N	50 Ns
25 grams	25 gram
25 g	25 gs
22 kelvins	22 kelvin
22 K	22 Ks

WRITING NUMBERS

Periods (not commas) are used as decimal markers. Numbers made up of five or more digits should be written with a space separating each group of three digits counting both to the left and right of the decimal point. With four digit numbers, the spacing is optional. Spaces (not commas) should be used between the groups of three digits. These conventions are illustrated below:

Correct	Incorrect
1 420 462.1	1,420,462.1
0.045 62	0.04562
1452 or 1 452	1,452

Numbers are expressed as decimals, not as fractions. The decimal should be preceded by a zero when the number is less than unity, as indicated below:

Correct	Incorrect
0.5 kg, 1.75 m	1/2 kg, .5 kg., 1 3/4 m

REPRESENTATION OF MATHEMATICAL OPERATIONS

A raised dot is used to indicate the product of two unit symbols. A space should be used to indicate the product of two unit names. Examples of preferred, nonpreferred, and incorrect forms are given below:

Preferred	Nonpreferred	Incorrect
newton meter (N·m)	newton-meter (N m)	newton·meter (N-m)

Symbols for derived units involving division may use a slanted line (solidus), a horizontal line, or negative exponents to indicate the division. No more than one solidus may be used in any unit combination unless parentheses are used to prevent ambiguity. In complicated cases, the use of negative exponents may be preferable to the use of the solidus (whether with or without parentheses). Numerical values should be adjusted so that the numerical value of the denominator is one. Examples of this convention follow:

Correct	Incorrect
m/s, $m \cdot s^{-1}$, 4 m/s	m/0.1 s, m/s/s
m/s^2, $m \cdot kg/(s^3 \cdot A)$	$M \cdot kg/s^3/A$, $kg/s/m^2$

The word *per* is used to indicate the quotient of two unit names, e.g., meter per second squared (m/s^2). An exponent is used with unit symbols to show powers, e.g., m^3. The words "square," "squared," and "cubic" are used with unit names to indicate powers, e.g., square meter (m^2), cubic meter (m^3), and second squared (s^2).

PUNCTUATION

Periods are not to be used after SI unit symbols except at the end of a sentence. Periods are not used in unit symbols or in conjunction with prefixes. These conventions are illustrated below:

Correct	Incorrect
5.7 mm	5.7 m.m., 5.7 mm.

TYPOGRAPHIC CONVENTIONS

A space is to be used between the numerical value and the unit symbol, as shown below:

Correct	Incorrect
4 mm	4mm

The symbols denoting SI units must be printed in Roman (upright) type. The symbols denoting quantities are preferably printed in italic (slanted) type. Examples of correct, nonpreferred, and incorrect type styles are presented below:

Correct	Nonpreferred	Incorrect
V = 87 V	V = 87 V	V = 87 V
I = 14 A	I = 14 A	I = 14 A
T = 200 °C	T = 200 °C	T = 200 $°C$

Two exceptions to the use of Latin alphabetic characters for SI symbols are the symbol "μ" for the prefix *micro* and the symbol "Ω" for the unit *ohm*. If circumstances prevent using these Greek letters, the symbol "u" can be used to denote *micro*, and the word *Ohm* can be used as the symbol for *ohm*. A hand-drawn tail should not be added on the "u"; it should be left as typewritten. An upper case "O" should be used in *Ohm* when it is used as a unit symbol, but not when used as a unit name. Examples are presented below:

Correct	Acceptable
4 um	4 microm
25 Ohm	25 Ohms
25 ohms	25 Ohms
17 Ohm/m	17 ohm/m, 17 Ohm/meter
17 ohms per meter	17 Ohm per meter

When it is necessary or desirable to use inch-pound units as the primary units in an equation or a table, SI units should be restated in a separate equation, table, or column in a table. As alternatives, (1) a note may be added to an equation or table giving the factors to be used in converting the calculated result in inch-pound to preferred SI units, or (2) the SI equivalents enclosed in parentheses or brackets may follow the inch-pound units.

CONVERSIONS

To convert units from the inch-pound system to SI, the conversion factors presented in Tables B.8 or B.9 can be applied, making use of the rounding rules discussed in the following sections. Alternatively, rational SI units can be applied; these often prevail in countries whose measurements have long been in metric units and appear in international standards (see Table B.6). The application of rational SI units is often guided by the use of preferred numbers to facilitate standardization (see the section "Preferred Numbers").

The strictly mathematical conversions are said to be "soft" conversions. Rational SI values are sometimes termed "hard" conversions. When used for the discussion of conversion methods, these terms are misleading and gradually losing favor.

When providing SI units to correspond to inch-pound units in AWS documents and the technical publications of other societies, the rational SI values generally follow the inch-pound units in parentheses or brackets, e.g., 70 ksi (480 MPa). For the so-called "soft" conversion, the "exact" SI values are shown is in parentheses, e.g., 70 ksi (483 MPa). It should be noted that the rational (or so-called "hard") conversions are not exact, and judgment must be applied especially when parts or components must fit, such as the case for filler metals requiring close contact when feeding through nozzles. The solution to the inexactness of the rational conversion can be accommodated by establishing tolerance ranges that overlap, allowing manufacturers to offer standard products that are sized to accommodate both SI and inch-pound usage.

RULES FOR CONVERTING AND ROUNDING

Converting and rounding are necessary only during a transition period. In manufacturing practice, this occurs most frequently when designing is done in SI units and fabrication must be done in inch-pound units. The necessity for conversion and rounding disappears when all steps can be performed in one system.

Exact conversion from one system to another usually results in numbers that are inconvenient to use. In addition, the intended precision is exaggerated when the conversion results in more decimal places than are necessary.

The degree of accuracy of the converted number is based on the intended or necessary precision of the product. The precision must be determined by the designer or user. The guidelines given herein may then be applied to arrive at appropriate numerical equivalents.

Table B.8
General Conversions

Quantity	To Convert From	To	Multiply By
acceleration (angular)	revolution per minute squared	rad/s^2	$1.745\ 329 \times 10^{-3}$
acceleration (linear)	$in./min^2$	m/s^2	$7.055\ 556 \times 10^{-6}$
	ft/min^2	m/s^2	$8.466\ 667 \times 10^{-5}$
	$in./min^2$	mm/s^2	$7.055\ 556 \times 10^{-3}$
	ft/s^2	m/s^2	$3.048\ 000 \times 10^{-1}$
angle, plane	deg	rad	$1.745\ 329 \times 10^{-2}$
	minute	rad	$2.908\ 882 \times 10^{-4}$
	second	rad	$4.848\ 137 \times 10^{-6}$
area	$in.^2$	m^2	$6.451\ 600 \times 10^{-4}$
	ft^2	m^2	$9.290\ 304 \times 10^{-2}$
	yd^2	m^2	$8.361\ 274 \times 10^{-1}$
	$in.^2$	mm^2	$6.451\ 600 \times 10^{2}$
	ft^2	mm^2	$9.290\ 304 \times 10^{4}$
	acre (U.S. survey)	m^2	$4.046\ 873 \times 10^{3}$
density	pound per cubic inch	kg/m^3	$2.767\ 990 \times 10^{4}$
	pound per cubic foot	kg/m^3	$1.601\ 846 \times 10$
energy, work, heat, and impact energy	foot pound-force	J	1.355 818
	foot poundal	J	$4.214\ 011 \times 10^{-2}$
	Btu*	J	$1.055\ 056 \times 10^{3}$
	calorie*	J	4.186 800
	watt hour	J	$3.600\ 000 \times 10^{3}$
force	kilogram-force	N	9.806 650
	pound-force	N	4.448 222
impact strength	(see energy)		
length	in.	m	$2.540\ 000 \times 10^{-2}$
	ft	m	$3.048\ 000 \times 10^{-1}$
	yd	m	$9.144\ 000 \times 10^{-1}$
	mile (statute)	m	$1.609\ 344 \times 10^{3}$
mass	pound (avoirdupois)	kg	$4.535\ 924 \times 10^{-1}$
	metric ton	kg	$1.000\ 000 \times 10^{3}$
	ton (short, 2000 lb)	kg	$9.071\ 847 \times 10^{2}$
	slug	kg	$1.459\ 390 \times 10$
power	horsepower (550 ft lbf/s)	W	$7.456\ 999 \times 10^{2}$
	horsepower (electric)	W	$7.460\ 000 \times 10^{2}$
	Btu/h*	W	$2.930\ 711 \times 10^{-1}$
	calorie per minute*	W	$6.976\ 333 \times 10^{-2}$
	foot pound-force per minute	W	$2.259\ 697 \times 10^{-2}$
pressure	psi	kPa	6.894 757
	bar	kPa	$1.000\ 000 \times 10^{2}$
	atmosphere	kPa	$1.013\ 250 \times 10^{2}$
	$kip/in.^2$	kPa	$6.894\ 757 \times 10^{3}$

(Continued)

Table B.8 (Continued)
General Conversions

Quantity	To Convert From	To	Multiply By
temperature	degree Celsius	K	$T_K = t_C + 273.15$
	degree Fahrenheit	K	$T_K = (t_F + 459.67)/1.8$
	degree Rankine	K	$T_K = T_R/1.8$
	degree Fahrenheit	°C	$t_C = (t_F - 32)/1.8$
	kelvin	°C	$t_C = T_K - 273.15$
temperature interval	degree Fahrenheit	K	0.555 555 6
	degree Rankine	K	0.555 555 6
	degree Fahrenheit	°C	0.555 555 6
tensile strength (stress)	ksi	MPa	6.894 757
torque	pound-force inch	N · m	$1.129\ 848 \times 10^{-1}$
	pound-force foot	N · m	1.355 818
velocity (angular)	revolution per minute	rad/s	$1.047\ 198 \times 10^{-1}$
	degree per minute	rad/s	$2.908\ 882 \times 10^{-4}$
	revolution per minute	deg/min	$3.600\ 000 \times 10^{2}$
velocity (linear)	in./min	m/s	$4.233\ 333 \times 10^{-4}$
	ft/min	m/s	$5.080\ 000 \times 10^{-3}$
	in./min	mm/s	$4.233\ 333 \times 10^{-1}$
	ft/min	mm/s	5.080 000
	mi/h	km/h	1.609 344
volume	$in.^3$	m^3	$1.638\ 706 \times 10^{-5}$
	ft^3	m^3	$2.831\ 685 \times 10^{-2}$
	yd^3	m^3	$7.645\ 549 \times 10^{-1}$
	$in.^3$	mm^3	$1.638\ 706 \times 10^{4}$
	ft^3	mm^3	$2.831\ 685 \times 10^{7}$
	$in.^3$	L	$1.683\ 706 \times 10^{-2}$
	ft^3	L	$2.831\ 685 \times 10$
	gallon (U.S.)	L	3.785 412

*Thermochemical.

INCH-TO-MILLIMETER CONVERSION

Exact conversion from inches to millimeters often results in unnecessarily long decimal numbers. Showing more decimal places than necessary leads to misinterpretation, uses valuable space, and increases the possibility of error. The numbers should be rounded to eliminate insignificant decimal places, consistent with the accuracy required. The rounding of equivalent millimeter dimensions should be handled as described here.

Nominal Dimensions

The closest practical indication of equivalent inch and millimeter values occurs when the millimeter value is shown to one less decimal place than its inch equivalent, e.g., 0.365 in. equals 9.27 mm. However, fractional inch conversions may exaggerate the intended precision. For example, the rule may not be applicable when changing 1 7/8 in. to 47.63 mm unless the precision of 1 7/8 in. was intended to be that of 1.875 in. Some dimensions must be converted more accurately to

Table B.9
Conversions for Common Welding Terms

Quantity	Inch-Pound	SI	Conversion Factor*
area dimensions	in.^{2}	mm^2	$6.451\ 600 \times 10^2$
current density	A/in.^{2}	A/mm^2	$1.550\ 003 \times 10^{-3}$
deposition rate	lb/h	kg/h	$4.535\ 924 \times 10^{-1}$
electrical resistivity	W · cm	W · m	$1.000\ 000 \times 10^{-2}$
flow rate	ft^3/h	L/min	$4.719\ 474 \times 10^{-1}$
	gallon per hour	L/min	$6.309\ 020 \times 10^{-2}$
	gallon per minute	L/min	3.785 412
fracture toughness	ksi · in.$^{1/2}$	MN · m$^{-3/2}$	1.098 843
	ksi · in.$^{1/2}$	MPa · m$^{1/2}$	1.098 843
heat input	J/in.	J/m	$3.937\ 008 \times 10$
impact energy absorption	foot pound-force	J	1.355 818
linear measurements	in.	mm	$2.540\ 000 \times 10$
	ft	mm	$3.048\ 000 \times 10^2$
power density	W/in.^{2}	W/m^2	$1.550\ 003 \times 10^3$
pressure (gas and liquid)	psi	kPa	6.894 757
	lbf/ft^2	kPa	$4.788\ 026 \times 10^{-2}$
	N/mm^2	kPa	$1.000\ 000 \times 10^3$
pressure (vacuum)	torr (mm Hg at 0°C)	Pa	$1.333\ 224\ 10^2$
	micron (µm Hg at 0°C)	Pa	$1.333\ 224 \times 10^{-1}$
tensile strength	psi	MPa	$6.894\ 757 \times 10^{-3}$
	lbf/ft^2	MPa	$4.788\ 026 \times 10^{-5}$
	N/mm^2	MPa	1.000 000
thermal conductivity	cal/(cm · s · °C)	W/(m · K)	$4.184\ 000 \times 10^2$
travel speed, wire feed speed	in./min	mm/s	$4.233\ 333 \times 10^{-1}$

*To convert from SI to inch-pound, multiply by the conversion factor. To convert from inch-pound to SI, divide by the conversion factor.

ensure the interchangeability of parts. The methods described in the section titled "Other Conversions" will accomplish this requirement.

Tolerances

The following round off criteria should be used when (1) it is necessary to ensure the physical and functional interchangeability of parts fabricated and inspected using either system of measurement and (2) when inch dimensions are converted to millimeter equivalents and shown on dual-dimensioned drawings:

1. *Basic and maximum-minimum dimensions.* Basic dimensions are inherently precise and should be converted exactly. When the function of a feature requires that the maximum and minimum limits in millimeters be within the inch limits, maximum limits are rounded down and minimum limits are rounded up;
2. *Dimensions without tolerance.* Untoleranced dimensions are converted to exact millimeter equivalents and rounded to equivalent or better precision, depending upon the purpose of the dimension; and
3. *Toleranced dimensions.* The normal practice for toleranced dimensions is to use Method A as described in the section "Round-Off Method A." However, when the function of a feature requires that the millimeter equivalents must be

within the inch dimension tolerance limits in all cases, Method B is used as described in the section "Round-Off Method B."

Number of Decimal Places in Tolerances. Table B.10 lists the criteria for retaining decimal places in millimeter equivalents to inch tolerances. The number of decimal places is determined by the inch tolerance span.

Round-Off Method A. Round-Off Method A produces rounded millimeter tolerances that vary from the inch tolerances by no more than 5%. Thus, for a dimension with a tolerance of 0.001 in., the maximum amount that the rounded millimeter can be greater or less than the inch tolerances is 0.000,050 in.

To calculate the millimeter equivalents of inch dimensions using Method A, these steps should be followed:

1. Determine the maximum and minimum limits in inches;
2. Determine the tolerance span in inches;
3. Convert the inch limit dimensions to millimeter values using exact millimeter equivalents; and
4. Based on the tolerance span in inches, (1) establish the number of decimal places to be retained by using Table B.10, and (2) round the millimeter values according to the rounding rules given in the section titled "Round-Off Rules." An example is presented in Table B.11.

Table B.10
Millimeter Value Round Off Using Inch Tolerance Span

Inch Tolerance Span			
At Least	**Less Than**	**Round Off Millimeter Value to These Decimal Places**	
0.000 04	0.0004	4 places	0.00XX
0.0004	0.004	3 places	0.0XX
0.004	0.04	2 places	0.XX
0.04	0.4	1 place	X.X
0.4 and over		Whole number	XX

Example: The span of a +0.005 in. to –0.003 in. tolerance is 0.008. Since 0.008 is between 0.004 and 0.04, two decimal places are retained in individually converting 0.005 and 0.003.

Table B.11
Comparison of Round-Off Methods A and B

Input	Inch dimensions: 1.934 in. to 1.966 in. Tolerance span: 0.032 in. Conversions: 1.934 in. = 49.1236 mm (exactly) 1.966 in. = 49.9364 mm (exactly) From Table B.10: 0.032 lies between 0.004 and 0.04; therefore, the millimeter values are to be rounded to two decimal places.
Method A	Rounding off 49.1236 and 49.9364 to two decimal places via the method shown in the section "Other Conversions" renders 49.12 mm and 49.94 mm, respectively. Method A renders a tolerance span of 0.82 mm.
Method B	Rounding to within the inch tolerance limits requires the 49.1236 mm limit to be rounded up, giving 49.13 mm as the lower limit, and the 49.9364 mm limit to be rounded down, giving 49.93 mm as the upper limit. Method B renders a tolerance span of 0.80 mm.
Difference between Methods A and B	The tolerance span of 0.32 in. = 0.8128 mm. In this example, Method A would increase the tolerance span by 0.0072 mm (0.88%), whereas Method B would decrease the tolerance span by 0.0128 mm (1.6%).

Round-Off Method B. Round-Off Method B is used when the resulting millimeter tolerances must be within the inch tolerances. In extreme cases, this method may result in the lower limit millimeter tolerance being greater than the lower inch tolerance by a maximum of 5%. Similarly, the upper limit millimeter tolerance may be smaller than the upper inch tolerance by a maximum of 5%. Thus, the tolerance span may be reduced by up to 10% of the original design inch tolerance; however, it is very unlikely that the 5% maximum will occur at both limits simultaneously.

To calculate the millimeter equivalents of inch dimensions using Method B, these steps should be followed:

1. Determine the maximum and minimum limits in inches;
2. Determine the tolerance span in inches;
3. Convert the inch tolerance to exact millimeter equivalents;
4. Based on the tolerance span in inches, establish the number of decimal places to be retained in the millimeter values using Table B.10; and
5. If rounding is required, round the millimeter values to fall within the inch tolerance limits, i.e., to the next lower value for the upper limit and to the next higher value for the lower limit. An example is presented in Table B.11.

OTHER CONVERSIONS

To establish meaningful and equivalent converted values, a careful determination must be made of the number of significant digits to be retained so as not to sacrifice or exaggerate the precision of the value. Converting a pressure of 1000 psi to 6.894 757 MPa is not practical because the value does not warrant expressing the conversion using six decimal places. Applying the convention presented in the section "Pressure or Stress Conversion," a practical conversion is 7 MPa. The intended precision of a value can be established from the specified tolerance or by an understanding of the equipment, process, or accuracy of the measuring device.

Values with a Specified Tolerance

A tolerance on a value provides a good indication of the intended precision. A general rule for determining the intended precision of a toleranced value is to assume that it is 1/10 of the total tolerance. Because the intended precision of the converted value should be no greater than that of the original, the total tolerance is divided by 10 and converted. The proper significant digits are retained in both the converted value and the converted tolerance so that the last significant digit retained is in units no larger than 1/10 the converted tolerance. The following examples illustrate this rule:

1. *200 ± 15 psi pressure converted to Pa.* The total tolerance is 30 psi. When this is divided by 10, a value of 3 psi results, which, when converted, is approximately 20.7 kPa. The unit to use is 10 kPa (rather than 1 kPa or 100 kPa) because 10 kPa is the largest unit smaller than 20.7 kPa, which is 1/10 the converted tolerance. Stated mathematically,

   200 ± 15 psi = 1378.9514 ± 103.421 355 kPa, which rounds to 1380 ± 100 kPa = 1.38 ± 0.10 MPa.

2. *25 ± 0.1 oz of alcohol converted to liters.* The total tolerance, 0.2 oz, divided by 10 is 0.02 oz, which, when converted, is approximately 0.6 mL. This units to use is 0.1 mL (rather than 10 mL or 1 mL). Stated mathematically,

   25 ± 0.1 oz = 739.34 ± 2.8957 mL, which rounds to 739.3 ± 2.9 mL.

Values with No Specified Tolerance

If a value is shown without a tolerance, the intended precision relates to the number of significant digits shown by assuming that the value had been rounded from a greater number of digits. The intended precision is established as being ± 1/2 unit of the last significant digit in which the value is stated. However, as the last significant digit moves away from the decimal point, the intended precision becomes distorted if this rule is used indiscriminately. In these cases, the intended precision is estimated as being some digit closer to the decimal point based on the nature of the value's use.

Because the intended precision of the converted value should be no greater than that of the original, the intended precision is established and converted. The proper significant digits are retained in the converted value so that the last significant digit retained is in units no larger than the converted intended precision. The following examples illustrate this policy:

1. *157 miles (rounded from any value between 156.5 and 157.5 miles) converted to kilometers.* The total intended precision is 1 mile, which is approximately 1.6 km. Thus,

   Unit to use: 1 km
   157 miles = 252.613 km, which rounds to 253 km.

2. *50,000 psi tensile strength converted to Pa.* The total estimated precision is 500 psi (3.4 MPa) from the nature of use and the precision of the measuring equipment. Thus,

Units to use: 1 MPa
50 000 psi = 344.7379 MPa, which rounds to 345 MPa.[5]

3. *8 ft long converted to meters.* The total intended precision is 1 ft, or about 0.3 m. Thus,

Unit to use: 0.1 m
8 ft = 2.4384 m, which rounds to 2.4 m.

Temperature

All temperatures expressed in whole numbers of degrees Fahrenheit are converted to the nearest 0.1 kelvin or degree Celsius. Fahrenheit temperatures indicated to be approximate, maximum, or minimum, or to have a tolerance of ± 5°F or more are converted to the nearest whole number in kelvins or degrees Celsius. Fahrenheit temperatures having a tolerance of ± 100°F or more are converted to the nearest 10 kelvins or degrees Celsius. Examples are presented below:

100 ± 5°F = 38 ± 3°C = 311 ± 3 K
1000 ± 100°F = 540 ± 40°C = 810 ± 40 K

Pressure or Stress Conversion

In most cases, stress values are converted from ksi to the nearest one MPa. Pressure or stress values having an uncertainty of more than 2% may be converted without rounding by the approximate factors, as shown below:

1 psi = 7 kPa   1 ksi = 7 MPa

ROUND-OFF RULES

When the digit following the last digit to be retained is less than five, the last digit retained is not changed. An example is presented below:

4.463 25 rounded to three decimal places is 4.463

When the digits following the last digit to be retained amount to more than five followed by zeros, the last digit retained is increased by one, as illustrated below:

8.376 52 rounded to three decimal places is 8.377

When the digit following the last digit to be retained is exactly five followed by zeros (expressed or implied), (1) if the last digit to be retained is even, it is unchanged, and (2) if the last digit to be retained is odd, it is increased by one. Examples are presented below:

4.365 00 becomes 4.36 when rounded to two decimal places

4.355 00 also becomes 4.36 when rounded to two decimal places

The final rounded value is obtained from the precise value to be rounded, not from a series of successive rounding. To maintain precision during conversion, the millimeter equivalent value is carried out to at least one extra decimal place. Generally, it is best to use exact values and round off only the final results.

TRANSITIONING TO SI

Most segments of U.S. society and industry will feel the impact of the metric conversion. Indeed, many companies are already implementing various phases of conversion. Some companies, particularly those with foreign interests, have completely converted. Others are maintaining an awareness of the state of metrication in the United States.

CONSIDERATIONS

A number of considerations must be weighed during the transition to SI units. These are discussed below.

Abrupt Changeover

The goal is to have engineers and designers "thinking metric" as quickly as possible. The experience in Great Britain has shown that learning to think metric is important in reducing transition time and costs and in gaining the benefits of the simpler, more rational SI system. This is especially so for engineers and designers who must think in groups of interrelated numbers and who depend on a "feel" for the design significance of these relationships. An abrupt change of engineering and design activities to SI is practical because this conversion involves the replacement of relatively low-cost equipment.

Replacement of Fabricating Equipment

Changing fabrication activities from inch-pound to SI units involves a large capital investment in equipment. In shops, transition time and cost can be short-

5. See the section "Pressure or Stress Conversion" for a less precise conversion.

ened somewhat by converting machine displays. Some machines are used only for nonprecision stock removal and need never be converted. Others, such as numerically controlled machines with digital displays, are electronically convertible.

Inspection gauges pertain to a special category; they last so long that cyclical replacement is not a practical way to convert inspection activities. In addition, inspection serves as a check on the other fabrication activities, including conversion errors. Therefore, it seems reasonable to convert gauges on a high-priority basis.

Cost-benefit considerations in the shop call for a more cyclical replacement approach with a completion goal consistent with average tool life. This means that the SI unit used by the engineering and design departments must be converted at the machine tool that still operates in inches. SI-to-inch-pound conversions must occur at some stage of the design-fabrication cycle while the machines are still working in the inch-pound system.

Dual Dimensioning

A popular way to handle the conversion of measurement is to employ dual dimensions on the drawings; however, side-by-side dual dimensioning (using parentheses or brackets) is a costly transition mechanism. Besides added drawing costs and increased drawing clutter, dual dimensioning allows engineers and designers to avoid learning to think metric because all the old familiar inch-pound numbers are provided. It is important that the transition period conversion mechanisms allow for gradual change as the need for conversion in the shop decreases.

Dual dimensioning at the design level can make for a costly transition mechanism until the last machine or vendor that must be dealt with is converted. As the purchase-fabricate decision is usually made after design work is complete, the designers seldom know where a drawing may go for fabrication and must treat every part as though it will be fabricated by machines operating in the inch-pound system.

One company considered several ideas and decided that the simplest and least costly way to handle the millimeter-inch conversion at the machine was to use a conversion table (see the section "Technique No. 1: Use of a One-Page Simplified Conversion Table Based on Preferred Dimensions"). This approach results in a dualism that decreases with time during the transition period. Dualism is less troublesome in shops where, for the most part, an operator is concerned with only one dimension at a time—the one being cut.

Converting Engineering Drawings to Shop Practice

The following techniques may be considered for dimensioning drawings. They are to be used only during a transition period. Ultimately, all dimensions will be in SI units, and all machine tools will have similar displays. The first technique involves the use of a conversion table that accompanies each drawing or is otherwise available to each user of the drawing. The second technique involves the inclusion of inch equivalents of millimeter dimensions in tabular form on each drawing. It should be noted that neither method involves side-by-side dual dimensioning.

Technique No. 1: Use of a One-Page Simplified Conversion Table Based on Preferred Dimensions. Supplying a conversion table to the machine operator becomes a more attractive idea if the table incorporates a system of preferred dimensions and tolerances that permits a simplified one-page table. Designers are expected to use the preferred numbers for dimensions and tolerances except in unusual cases. Since both designers and fabricators use the same simplified table, the engineer/designer should have confidence in the conversion of the millimeter dimension for fabrication and inspection. The few numbers on a drawing not covered by the table are converted by the designer and placed in a corner of the drawing.

The success of this approach is measured by how few numbers on a drawing are not from the preferred list. If too many of the numbers on a drawing are converted on the drawing, this method becomes a form of dual dimensioning.

Technique No. 2: Inclusion of a Conversion Chart on Each Drawing. In this method, millimeter-to-inch conversions are included in tabular form on new drawings. Only the dimensions appearing on the drawing are given, usually in order of magnitude. One approach is to use computer-generated conversion charts that are copied onto adhesive-backed transparent sheets. The charts are then attached to the original drawings for copying. Similar charts can be attached to existing drawings' vellums along with a prominent "METRIC" label. The "Change" block would reflect the revision, and the drawings would be reissued.

Replacing Existing Inch-Pound Inventory with Metric Inventory

No attempt should be made to use raw materials and supplies produced with metric units if doing so degrades some design or fabrication factor, including cost. In addition, materials should be called out on metric drawings as they are fabricated and specified, i.e., SI units should be used for metric materials, and inch-pound units should be used to define materials fabricated using inch-pound units. The entire inventory of supplies should be monitored to introduce metric supplies on a timely basis. It is also important to have information on the availability of metric materials as early as possible to prepare for the change in inventory and design.

Preferred Number Approach for General Inventory Reduction

A possible inventory reduction plan would designate preferred items within the existing inventory to the engineering and design departments. Item usage would then be monitored to determine which, if any, of the nonpreferred items should be added to the preferred list. All remaining nonpreferred items would be eliminated from the inventory. It is important that the monitoring procedure be sensitive to the possible use of preferred items at the expense of design integrity.

The attractiveness of the preferred-list approach to inventory reduction is that design requirements can be tested before a firm position must be taken on which items will be eliminated from the inventory (see the section "Preferred Numbers"). The success of this approach depends upon the extent to which an existing inventory can be pruned without significant loss of fabrication efficiency.

Training

Formal classroom training can provide background information on the basics of SI and for inspirational purposes. During formal training, reference material should be provided for self-teaching. The tendency to overdo the training aspects of metric conversion beyond what is economical should be avoided. SI is a simple system, and individuals initially need to learn only the portion of SI that pertains to their discipline.

Standard Practices

The necessary policy and procedures should be provided by the issuance of a metric engineering standard. This standard will serve to coordinate efforts and assure that common practices are used.

PREFERRED NUMBERS

Preferred numbers are a series of numbers recommended as an aid to establish sizes, such as the sizes of bolts, electrodes, fillet welds, and so on, when a range of sizes is desired. These series are designed according to a geometric progression. Each number in the series has the same proportional relationship to its preceding number. For general purposes of sizing and grading, a geometric series is usually more rational than an arithmetically progressive series.

In an arithmetic series, the unit size increment is constant for any range of sizes. An example of the customary arithmetic progression is fractional drive (or hole) sizes that are in size increments of 1/64 in. The fineness of the division gets ridiculously small as the nominal diameter increases to 1 in. or more.

APPLICATION OF PREFERRED NUMBERS

The size of the increments in a geometric series is determined by a multiplying factor that in the most common series used in the mechanical field (the Renard series) is a root of 10. The Preferred Number 5, 10, 20, and 40 Series are the most commonly used preferred number series. These cover the majority of applications. One series is selected from this group for a given standard, according to the size or number of increments desired.

The basis for the preferred number system is as follows. The number 1.0 is used as the first number of a series. Each succeeding number is determined by multiplying its preceding number by a constant factor for the series. The product is rounded to measurable values, consistent with the characteristics for which a standard is being established. Constant factors are determined as follows:

For the 5 Series: $\sqrt[5]{10}$, or 1.5849

For the 10 Series: $\sqrt[10]{10}$, or 1.2589

For the 20 Series $\sqrt[10]{10}$, or 1.1220

For the 40 Series $\sqrt[10]{10}$, or 1.0593

In the 5 Series, succeeding numbers represent an increase of approximately 60% over the preceding number; in the 10 Series, approximately 25%; in the 20 Series, approximately 12%; and in the 40 series, approximately 6%. The progressively larger steps within a preferred number series result in fewer sizes within the overall range of a product or material line. This can mean savings in such items as development, tooling, setup time, and stock keeping. The 5-, 10-, 20-, and 40-Series preferred numbers are shown in Table B.12.

The numbers in Table B.12 are approximations of the theoretical values thus obtained, the departure from the theoretical values being no more than 1.3%. The theoretical values are not given here because they are of no value in the practical application of the system. A table of the "exact" numbers (five decimals) is given in the standard *Preferred Numbers—Series of Preferred Numbers,* ISO 3:1973.[6]

6. International Organization for Standardization (ISO), 1973, *Preferred Numbers—Series of Preferred Numbers,* ISO 3:1973, Geneva: International Organization for Standardization.

Table B.12
Basic Preferred Numbers—Decimal Series (1 to 10)

5 Series (60% steps)	10 Series (25% steps)	20 Series (12% steps)	40 Series (6% steps)
1.0	1.0	1.0	1.0
			1.06
		1.12	1.12
			1.18
	1.25	1.25	1.25
			1.32
		1.4	1.4
			1.5
1.6	1.6	1.6	1.6
			1.7
		1.8	1.8
			1.9
	2.0	2.0	2.0
			2.12
		2.24	2.24
			2.36
2.5	2.5	2.5	2.5
			2.65
		2.8	2.8
			3.0
	3.15	3.15	3.15
			3.35
		3.55	3.55
			3.75
4.0	4.0	4.0	4.0
			4.25
		4.5	4.5
			4.75
	5.0	5.0	5.0
			5.3
		5.6	5.6
			6.0
6.3	6.3	6.3	6.3
			6.7
		7.1	7.1
			7.5
	8.0	8.0	8.0
			8.5
		9.0	9.0
			9.5

Note: Percentage steps are approximate averages.

As an example of the application of the preferred number concept, the Preferred Number 10 Series was used to determine the appropriate rational sizes of fillet welds given in the column headed "Rational Series" in Table B.7. In this case, the series was started at 3 mm (approximately equal to a 1/8 in. fillet). The value of 3 mm was rounded from the table value of 3.15 mm as a practical consideration. From there on, the sizes 4, 5, 6, 8, and so on result in approximately 25% increase per step. It should be noted that the 13 mm size is superfluous and is not used.

VALUE OF USING PREFERRED NUMBERS

The adoption of a series of preferred numbers to be used by all designers tends to unify sizes chosen by different designers, reduce the variety of numbers used, and create the uniformity and consequent interchangeability that are indispensable to successful standardization work.

For those working toward the development of metric industrial standards and hoping for possible international acceptance, adherence to the concept of preferred numbers is strongly recommended. To secure acceptance from the International Organization for Standardization (ISO) for a standard in a mechanical field such as welding, the suggested grading should be consistent with the concept of preferred numbers. For example, a major U.S. producer of roller bearings was forced to change the sizes of a new metric line of roller bearings consistent with a preferred number series as part of an effort to make the suggested standard more acceptable to ISO.

Preferred numbers are recommended for use by smaller industrial units or by individuals wishing to establish rational standardization for their own activities in order to maintain compatibility with eventual national or international standards.

Changing nonconforming standards that are well established and generally satisfactory requires an evaluation of the advantages and disadvantages in each case. Changes made merely for the purpose of conforming to the preferred number system may not be justifiable in the face of economic disadvantage. Appropriate activity in each situation will be determined by the responsible agency or the agency's committee.

Serious consideration should be given to the use of preferred numbers for any extension of an existing nonconforming standard. Converting to a preferred numbers system over a transition period may be advantageous for some standards. More details of preferred numbers with applications and approximate calculations can be found in the standards *Preferred Numbers—Series of Preferred Numbers*, ISO 3,[7] *Guide to the Use of Preferred Numbers and of Series of Preferred Numbers*, ISO 17,[8] and *Guide to the Choice of Preferred Numbers and of Series Containing More Rounded Values of Preferred Numbers*, ISO 497.[9]

7. See Reference 6.
8. International Organization for Standardization (ISO), *Guide to the Use of Preferred Numbers and of Series of Preferred Numbers*, ISO 17, Geneva: International Organization for Standardization.
9. International Organization for Standardization (ISO), *Guide to the Choice of Preferred Numbers and of Series Containing More Rounded Values of Preferred Numbers*, ISO 497, Geneva: International Organization for Standardization.

CONVERSION TABLES

This section presents various tables to assist in converting from inch-pound units to SI units (see Tables B.13, B.14, and B.15).

Table B.13
Inch-to-Millimeter Conversions

1 in. = 25.4 mm exactly
To convert decimal inches to millimeters, multiply the inch value by 25.4.
To convert decimal millimeters to inches, divide the millimeter value by 25.4.

Inch			Inch		
Fractional	Decimal	Millimeter	Fractional	Decimal	Millimeter
1/64	0.016	0.397	33/64	0.516	13.097
1/32	0.031	0.794	17/32	0.531	13.494
3/64	0.047	1.191	35/64	0.547	13.891
1/16	0.062	1.588	9/16	0.562	14.288
5/64	0.078	1.984	37/64	0.578	14.684
3/32	0.094	2.381	19/32	0.594	15.081
7/64	0.109	2.778	39/64	0.609	15.478
1/8	0.125	3.175	5/8	0.625	15.875
9/64	0.141	3.572	41/64	0.641	16.272
5/32	0.156	3.969	21/32	0.656	16.669
11/64	0.172	4.366	43/64	0.672	17.066
3/16	0.188	4.762	11/16	0.688	17.462
13/64	0.203	5.159	45/64	0.703	17.859
7/32	0.219	5.556	23/32	0.719	18.256
15/64	0.234	5.953	47/64	0.734	18.653
1/4	0.250	6.350	3/4	0.750	19.050
17/64	0.266	6.747	49/64	0.766	19.447
9/32	0.281	7.144	25/32	0.781	19.844
19/64	0.297	7.541	51/64	0.797	20.241
5/16	0.312	7.938	13/16	0.813	20.638
21/64	0.328	8.334	53/64	0.828	21.034
11/32	0.344	8.731	27/32	0.844	21.431
23/64	0.359	9.128	55/64	0.859	21.828
3/8	0.375	9.525	7/8	0.875	22.225
25/64	0.391	9.922	57/64	0.891	22.622
13/32	0.406	10.319	29/32	0.906	23.019
27/64	0.422	10.716	59/64	0.922	23.416
7/16	0.438	11.112	15/16	0.938	23.813
29/64	0.453	11.509	61/64	0.953	24.209
15/32	0.469	11.906	31/32	0.969	24.606
31/64	0.484	12.303	63/64	0.984	25.003
1/2	0.500	12.700	1	1.000	25.400

Table B.14
Pound-Force per Square Inch (psi) to Kilopascal (kPa) Conversions
Thousand Pound-Force per Square Inch (ksi) to Megapascal (MPa) Conversions

1 psi = 6894.757 Pa
To convert psi to Pa, multiply the psi value by $6.894\,757 \times 10^3$
To convert Pa to psi, divide the Pa value by $6.894\,757 \times 10^3$

psi ksi	kPa MPa	psi ksi	kPa MPa	psi ksi	kPa MPa	psi ksi	kPa MPa
1	6.90	26	179	51	352	76	524
2	13.8	27	186	52	359	77	531
3	20.7	28	193	53	365	78	538
4	27.6	29	200	54	372	79	545
5	34.5	30	207	55	379	80	552
6	41.4	31	214	56	386	81	558
7	48.3	32	221	57	393	82	565
8	55.2	33	228	58	400	83	572
9	62.1	34	234	59	407	84	579
10	68.9	35	241	60	414	85	586
11	75.8	36	248	61	421	86	593
12	82.7	37	255	62	427	87	600
13	89.6	38	262	63	434	88	607
14	96.5	39	269	64	441	89	614
15	103	40	276	65	448	90	621
16	110	41	283	66	455	91	627
17	117	42	290	67	462	92	634
18	124	43	296	68	469	93	641
19	131	44	303	69	476	94	648
20	138	45	310	70	483	95	655
21	145	46	317	71	490	96	662
22	152	47	324	72	496	97	669
23	159	48	331	73	503	98	676
24	165	49	338	74	510	99	683
25	172	50	345	75	517	100	689

Table B.15
Fahrenheit-Celsius Temperature Conversions

$t_C = (t_F - 32)/1.8 \qquad t_F = (1.8\ t_C) + 32$

Find the number to be converted (regardless of its temperature scale) in the center (boldface) column.
If converting from Fahrenheit degrees, read the Celsius equivalent in the column headed "°C."
If converting from Celsius degrees, read the Fahrenheit equivalent in the column headed "°F."

°C	Number to Be Converted	°F	°C	Number to Be Converted	°F	°C	Number to Be Converted	°F	°C	Number to Be Converted	°F
−273	**−459**		−23	**−10**	14	31	**88**	190	254	**490**	914
−268	**−450**		−18	**0**	32	32	**90**	194	260	**500**	932
−262	**−440**		−17	**2**	36	33	**92**	198	266	**510**	950
−257	**−430**		−16	**4**	39	34	**94**	201	271	**520**	968
−251	**−420**		−14	**6**	43	36	**96**	205	277	**530**	986
−246	**−410**		−13	**8**	46	37	**98**	208	282	**540**	1004
−240	**−400**		−12	**10**	50	38	**100**	212	288	**550**	1022
−234	**−390**		−11	**12**	54	43	**110**	230	293	**560**	1040
−229	**−380**		−10	**14**	57	49	**120**	248	299	**570**	1058
−223	**−370**		−9	**16**	61	54	**130**	266	304	**580**	1076
−218	**−360**		−8	**18**	64	60	**140**	284	310	**590**	1094
−212	**−350**		−7	**20**	68	66	**150**	302	316	**600**	1112
−207	**−340**		−6	**22**	72	71	**160**	320	321	**610**	1130
−201	**−330**		−4	**24**	75	77	**170**	338	327	**620**	1148
−196	**−320**		−3	**26**	79	82	**180**	356	332	**630**	1166
−190	**−310**		−2	**28**	82	88	**190**	374	338	**640**	1184
−184	**−300**		−1	**30**	86	93	**200**	392	343	**650**	1202
−179	**−290**		0	**32**	90	99	**210**	410	349	**660**	1220
−173	**−280**		1	**34**	93	104	**220**	428	354	**670**	1238
−168	**−270**	−454	2	**36**	97	110	**230**	446	360	**680**	1256
−162	**−260**	−436	3	**38**	100	116	**240**	464	366	**690**	1274
−157	**−250**	−418	4	**40**	104	121	**250**	482	371	**700**	1292
−151	**−240**	−400	6	**42**	108	127	**260**	500	377	**710**	1310
−146	**−230**	−382	7	**44**	111	132	**270**	518	382	**720**	1328
−140	**−220**	−364	8	**46**	115	138	**280**	536	388	**730**	1346
−134	**−210**	−346	9	**48**	118	143	**290**	554	393	**740**	1364
−129	**−200**	−328	10	**50**	122	149	**300**	572	399	**750**	1382
−123	**−190**	−310	11	**52**	126	154	**310**	590	404	**760**	1400
−118	**−180**	−292	12	**54**	129	160	**320**	608	410	**770**	1418
−112	**−170**	−274	13	**56**	133	166	**330**	626	416	**780**	1436
−107	**−160**	−256	14	**58**	136	171	**340**	644	421	**790**	1454
−101	**−150**	−238	16	**60**	140	177	**350**	662	427	**800**	1472
−96	**−140**	−220	17	**62**	144	182	**360**	680	432	**810**	1490
−90	**−130**	−202	18	**64**	147	188	**370**	698	438	**820**	1508
−84	**−120**	−184	19	**66**	151	193	**380**	716	443	**830**	1526
−79	**−110**	−166	20	**68**	154	199	**390**	734	449	**840**	1544
−73	**−100**	−148	21	**70**	158	204	**400**	752	454	**850**	1562
−68	**−90**	−130	22	**72**	162	210	**410**	770	460	**860**	1580
−62	**−80**	−112	23	**74**	165	216	**420**	788	466	**870**	1598
−57	**−70**	−94	24	**76**	169	221	**430**	806	471	**880**	1616
−51	**−60**	−76	26	**78**	172	227	**440**	824	477	**890**	1634
−46	**−50**	−58	27	**80**	176	232	**450**	842	482	**900**	1652
−40	**−40**	−40	28	**82**	180	238	**460**	860	488	**910**	1670
−34	**−30**	−22	29	**84**	183	243	**470**	878	493	**920**	1688
−29	**−20**	−4	30	**86**	187	249	**480**	896	499	**930**	1706

(Continued)

Table B.15 (Continued)
Fahrenheit-Celsius Temperature Conversions

$t_C = (t_F - 32)/1.8$ $t_F = (1.8\ t_C) + 32$

Find the number to be converted (regardless of its temperature scale) in the center (boldface) column.
If converting from Fahrenheit degrees, read the Celsius equivalent in the column headed "°C."
If converting from Celsius degrees, read the Fahrenheit equivalent in the column headed "°F."

°C	Number to Be Converted	°F	°C	Number to Be Converted	°F	°C	Number to Be Converted	°F	°C	Number to Be Converted	°F
504	**940**	1724	754	**1390**	2534	1004	**1840**	3344	1254	**2290**	4154
510	**950**	1742	760	**1400**	2552	1010	**1850**	3362	1260	**2300**	4172
516	**960**	1760	766	**1410**	2570	1016	**1860**	3380	1266	**2310**	4190
521	**970**	1778	771	**1420**	2588	1021	**1870**	3398	1271	**2320**	4208
527	**980**	1796	777	**1430**	2606	1027	**1880**	3416	1277	**2330**	4226
532	**990**	1814	782	**1440**	2624	1032	**1890**	3434	1282	**2340**	4244
538	**1000**	1832	788	**1450**	2642	1038	**1900**	3452	1288	**2350**	4262
543	**1010**	1850	793	**1460**	2660	1043	**1910**	3470	1293	**2360**	4280
549	**1020**	1868	799	**1470**	2678	1049	**1920**	3488	1299	**2370**	4298
554	**1030**	1886	804	**1480**	2696	1054	**1930**	3506	1304	**2380**	4316
560	**1040**	1904	810	**1490**	2714	1060	**1940**	3524	1310	**2390**	4334
566	**1050**	1922	816	**1500**	2732	1066	**1950**	3542	1316	**2400**	4352
571	**1060**	1940	821	**1510**	2750	1071	**1960**	3560	1321	**2410**	4370
577	**1070**	1958	827	**1520**	2768	1077	**1970**	3578	1327	**2420**	4388
582	**1080**	1976	832	**1530**	2786	1082	**1980**	3596	1332	**2430**	4406
588	**1090**	1994	838	**1540**	2804	1088	**1990**	3614	1338	**2440**	4424
593	**1100**	2012	843	**1550**	2822	1093	**2000**	3632	1343	**2450**	4442
599	**1110**	2030	849	**1560**	2840	1099	**2010**	3650	1349	**2460**	4460
604	**1120**	2048	854	**1570**	2858	1104	**2020**	3668	1354	**2470**	4478
610	**1130**	2066	860	**1580**	2876	1110	**2030**	3686	1360	**2480**	4496
616	**1140**	2084	866	**1590**	2894	1116	**2040**	3704	1366	**2490**	4514
621	**1150**	2102	871	**1600**	2912	1121	**2050**	3722	1371	**2500**	4532
627	**1160**	2120	877	**1610**	2930	1127	**2060**	3740	1377	**2510**	4550
632	**1170**	2138	882	**1620**	2948	1132	**2070**	3758	1382	**2520**	4568
638	**1180**	2156	888	**1630**	2966	1138	**2080**	3776	1388	**2530**	4586
643	**1190**	2174	893	**1640**	2984	1143	**2090**	3794	1393	**2540**	4604
649	**1200**	2192	899	**1650**	3002	1149	**2100**	3812	1399	**2550**	4622
654	**1210**	2210	904	**1660**	3020	1154	**2110**	3830	1404	**2560**	4640
660	**1220**	2228	910	**1670**	3038	1160	**2120**	3848	1410	**2570**	4658
666	**1230**	2246	916	**1680**	3056	1166	**2130**	3866	1416	**2580**	4676
671	**1240**	2264	921	**1690**	3074	1171	**2140**	3884	1421	**2590**	4694
677	**1250**	2282	927	**1700**	3092	1177	**2150**	3902	1427	**2600**	4712
682	**1260**	2300	932	**1710**	3110	1182	**2160**	3920	1432	**2610**	4730
688	**1270**	2318	938	**1720**	3128	1188	**2170**	3938	1438	**2620**	4748
693	**1280**	2336	943	**1730**	3146	1193	**2180**	3956	1443	**2630**	4766
699	**1290**	2354	949	**1740**	3164	1199	**2190**	3974	1449	**2640**	4784
704	**1300**	2372	954	**1750**	3182	1204	**2200**	3992	1454	**2650**	4802
710	**1310**	2390	960	**1760**	3200	1210	**2210**	4010	1460	**2660**	4820
716	**1320**	2408	966	**1770**	3218	1216	**2220**	4028	1466	**2670**	4838
721	**1330**	2426	971	**1780**	3236	1221	**2230**	4046	1471	**2680**	4856
727	**1340**	2444	977	**1790**	3254	1227	**2240**	4064	1477	**2690**	4874
732	**1350**	2462	982	**1800**	3272	1232	**2250**	4082	1482	**2700**	4892
738	**1360**	2480	988	**1810**	3290	1238	**2260**	4100	1488	**2710**	4910
743	**1370**	2498	993	**1820**	3308	1243	**2270**	4118	1493	**2720**	4928
749	**1380**	2516	999	**1830**	3326	1249	**2280**	4136	1499	**2730**	4946

(Continued)

Table B.15 (Continued)
Fahrenheit-Celsius Temperature Conversions

$t_C = (t_F - 32)/1.8$ $t_F = (1.8\ t_C) + 32$

Find the number to be converted (regardless of its temperature scale) in the center (boldface) column.
If converting from Fahrenheit degrees, read the Celsius equivalent in the column headed "°C."
If converting from Celsius degrees, read the Fahrenheit equivalent in the column headed "°F."

°C	Number to Be Converted	°F	°C	Number to Be Converted	°F	°C	Number to Be Converted	°F	°C	Number to Be Converted	°F
1504	**2740**	4964	1543	**2810**	5090	1582	**2880**	5216	1621	**2950**	5342
1510	**2750**	4982	1549	**2820**	5108	1588	**2890**	5234	1627	**2960**	5360
1516	**2760**	5000	1554	**2830**	5126	1593	**2900**	5252	1632	**2970**	5378
1521	**2770**	5018	1560	**2840**	5144	1599	**2910**	5270	1638	**2980**	5396
1527	**2780**	5036	1566	**2850**	5162	1604	**2920**	5288	1643	**2990**	5414
1532	**2790**	5054	1571	**2860**	5180	1610	**2930**	5306	1649	**3000**	5432
1538	**2800**	5072	1577	**2870**	5198	1616	**2940**	5324			

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