Welding Technology

By Roger Cantrell

Learning Objectives

This course introduces the student to the concept of developing procedures for welding and brazing. Welding and brazing variables are introduced and some example concepts for applying each variable are highlighted to pique the student's interest and perhaps lead to further study. Upon completion of this course, the student should be able to:

- Understand the concept of creating a welding/brazing procedure
- Identify several commonly used welding/brazing processes
- Identify the more common welding/brazing variables
- Appreciate some of the considerations for applying each variable

1.0 INTRODUCTION

This course highlights the basic concepts of developing a welding or brazing procedure specification (WPS/BPS). There are a number of ways to approach this subject such as by process, base material, etc. It will be convenient to organize our thoughts in the format of ASME Section IX. The various factors that might influence weld quality are identified in ASME Section IX as "Welding Variables". "Brazing Variables" are treated in a separate part of Section IX in a manner similar to welding variables.

The listing of variables for welding procedures can be found in ASME Section IX, Tables QW-252 through QW-265 (a table for each process). The layout of each table is similar to Figure No. 1.

Process				
Variable	Variation (Description)	Essential	Supplementary Essential	Nonessential
Joint	Backing			X
	Root Spacing		X	
Base Metal	P Number	X		
	G Number		X	
Filler Metal	F Number	X		
	A Number		X	
Continued in this fashion until all relevant variables for the subject process are listed.				

Figure No. 1

Generalized Layout of ASME Section IX Tables of Welding Variables (For actual tables, see ASME Section IX, QW-252 to QW-265 for the Applicable Process)

The actual variables in each table will change with the nature of the process, e.g. the table for oxyacetylene welding does not include electrical characteristics. These Tables are summaries, i.e. they reference more detailed descriptions of the variables in other parts of Section IX. Each applicable variable listed in these tables must be addressed in the welding or brazing procedure specification (WPS or BPS). Additionally, variables designated "Essential" must also be addressed in a procedure qualification, a laboratory verification of the procedure's ability to produce sound welds when applied by a qualified welder. If the base material has toughness requirements specified by the Construction Code, there are additional "Supplementary Essential" variables to address. It is important to note that other Sections of the ASME Boiler and Pressure Vessel Code may specify additional variables beyond Section IX for special cases. Most other welding codes use a similar concept. Some, such as AWS D1.1, eliminate the procedure qualification requirement for specific, well-defined situations.

A Section IX welding or brazing procedure is "built" by taking each applicable variable in turn and defining a "value" or "answer" for it. The effects of each variable by itself and its interrelation to the other variables must be considered. This course highlights some of these variables to present a background for welding and brazing procedure development.

2.0 BASIC PROCESSES

There exist a multitude of welding and brazing processes. The sixteen examples below are just a few of hundreds defined by the American Welding Society.

Atomic Hydrogen Welding (AHW)	Carbon Arc Welding (CAW)
Shielded Metal Arc Welding (SMAW)	Explosion Welding (EXW)
Electrogas Welding (EGW)	Gas Tungsten Arc Welding (GTAW)
Stud Arc Welding (SW)	Submerged Arc Welding (SAW)
Oxyacetylene Welding (OAW)	Torch Brazing (TB)
Flux Cored Arc Welding (FCAW)	Gas Metal Arc Welding (GMAW)
Friction Welding (FRW)	Thermit Welding (TW)
Plasma Arc Welding (PAW)	Forge Welding (FOW)

AND MANY MORE

For brevity, we will discuss only shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), flux cored arc welding (FCAW), stud arc welding (SW), oxyacetylene welding (OAW), torch brazing (TB), braze welding (BW), gas metal arc welding (GMAW), and Cadwelding. The American Welding Society (AWS) definition of these processes and some commentary follows. Sketches of most processes can be found in the "Welding Handbook" published by the American Welding Society.

Shielded metal arc welding (SMAW) "An arc welding process which produces coalescence of metals by heating them with an arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode".

There are two variations of this process distinguished by the type of electrode covering.

Cellulosic (C) coated electrodes provide a predominantly gaseous shielding of carbon monoxide, carbon dioxide, hydrogen, and water vapor resulting from decomposition of the organic cellulosic covering. Low hydrogen (LH) electrodes provide a predominantly liquid (slag) shielding avoiding the hydrogen resulting from decomposition of a cellulosic coating. Due to danger of hydrogen cracking, cellulosic covered electrodes in general are limited to thinner-section, lower-alloy ferrous materials where they find wide use for open root joints and moderately oxidized (rusted) base metals.

Gas tungsten arc welding (GTAW) "An arc welding process which produces coalescence of metals by heating them with an arc between a tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture. Pressure may or may not be used and filler metal may or may not be used".

The manual GTAW process is generally considered suitable for low-production, high-quality requirement applications. This process finds considerable application for the root pass of open root joints as an alternative to cellulose coated electrodes or where cellulose coated electrodes are not suitable.

Flux cored arc welding (FCAW) "An arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is provided by a flux contained within the tubular electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture".

FCAW is generally considered a high productivity process and therefore is frequently applied when a significant volume of welding is required. ASME Section IX considers FCAW a variation of Gas Metal Arc Welding (GMAW) which is a similar process using solid wire and external gas shielding.

Stud arc welding (SW) "An arc welding process which produces coalescence of metals by heating them with an arc between a metal stud, or similar part, and the other work part. When the surfaces to be joined are properly heated, they are brought together under pressure. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud. Shielding gas flux may or may not be used".

Stud welding is a rapid process requiring very little welder skill, but specialized stud welding equipment is required.

Oxyacetylene welding (OAW) "An oxyfuel gas welding process which produces coalescence of metals by heating them with a gas flame or flames obtained from the combustion of acetylene with oxygen. The process may be used with or without the application of pressure and with or without the use of filler metal".

ASME Section IX considers OAW a variation of OFW (oxyfuel welding).

Brazing "A group of welding processes which produce coalescence of materials by heating them to a suitable temperature and by using a filler metal having a liquidus above 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". Torch brazing (TB) is further defined as "a brazing process in which the heat required is furnished by a fuel gas flame".

ASME Section IX treats brazing in a separate part (part QB) from welding. The distinction between brazing and soldering is arbitrarily set by AWS as whether the filler metal melts above or below 840°F. The term “silver soldering” is sometimes incorrectly used. Silver based filler metals melt above 840°F so the correct term is “silver brazing”.

Braze welding (BW) "A welding process variation in which a filler metal, having a liquidus above 840°F and below the solidus of the base metal, is used. Unlike brazing, in braze welding the filler metal is not distributed in the joint by capillary action".

Braze welding is a somewhat unique process not addressed by ASME Section IX, but is an excellent method for repairing cast iron.

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".

GMAW has four metal transfer modes, short circuiting (short arc), globular, spray, and pulsed spray (a variation of spray transfer). The transfer mode depends on the shielding gas and current density. GMAW produces high quality welds with proper welding procedures. Because there is no flux covering on the electrode, the possibility of slag inclusions is lessened. GMAW is an all position welding process, depending on the electrode and gas(es) used. It can be used to weld most metals and a variety of thicknesses.

Cadwelding - AWS and ASME Section IX do not specifically address Cadwelding. Cadwelding is an exothermic braze welding process which creates copper to copper or copper to steel electrical connections in which no outside source of heat or power is required. Other applications include splicing reinforcing bars and railroad rails. Powdered metals (copper oxide and aluminum) are placed into a graphite crucible and ignited to form the joint.

3.0 JOINT TYPE/ WELD TYPE

The terms "joint" and "weld" are frequently used interchangeably, creating a source of confusion. A "joint" is the geometric relationship of the base metal pieces to each other. The five joint types (butt, corner, T, lap, and edge) are illustrated in Figure No. 2. The joint type is frequently dictated by the design requirements of the item to be fabricated.

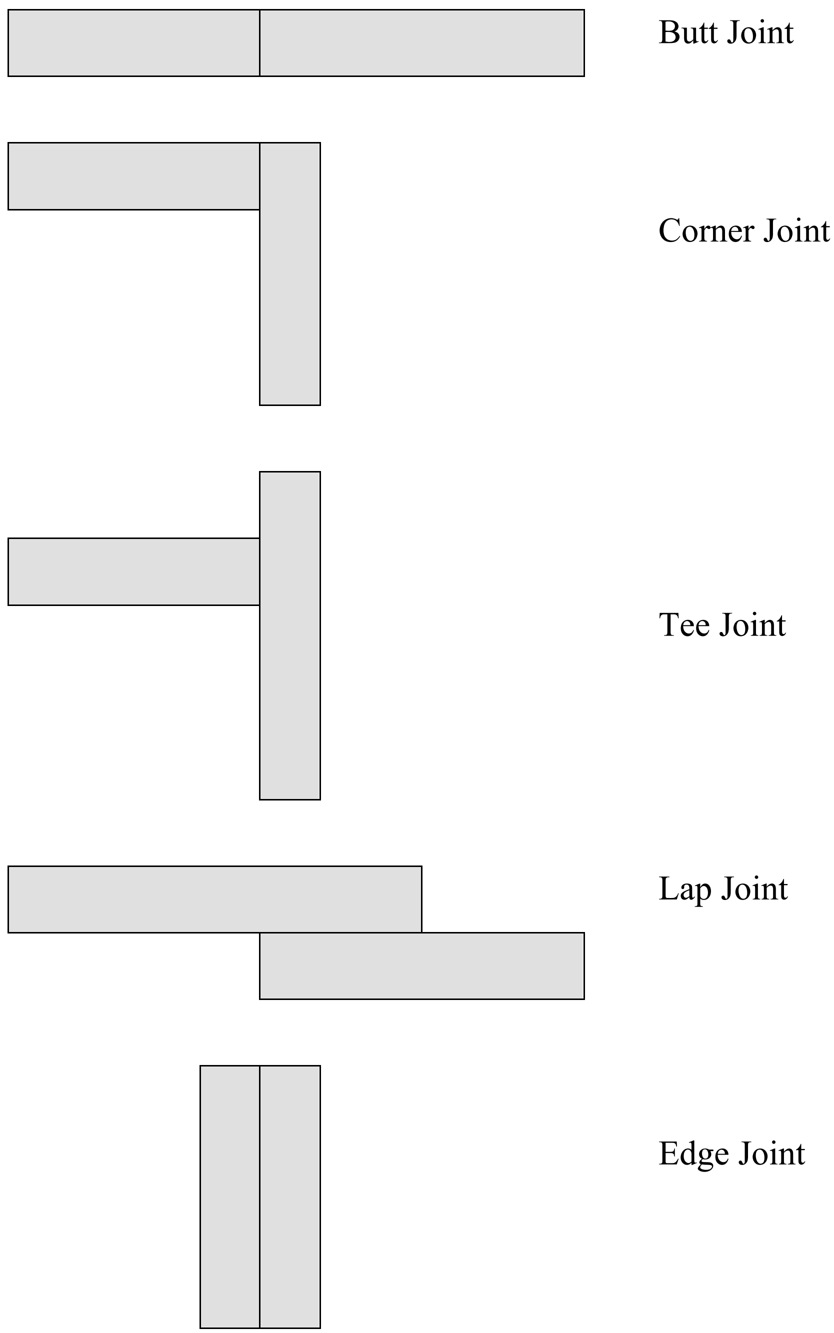


Figure No. 2

The Five Basic Joint Types

A "weld" or "braze" is the fused material which holds the base metal pieces in the geometric relationship of the joint. For example, a socket weld is actually a lap joint assembled with a fillet weld. The fused material may consist of base metal alone as occurs in an autogenous weld (a weld made without filler metal), base metal and filler metal together which is the usual case, or filler metal alone as occurs in brazing (where base metal is not melted). Usually any of a number of "weld" types may be used for a given "joint" type. The design portion of governing codes will usually address the permissible weld types for various joint types. Structural welds are fillet welds or groove welds. Special welds serve some purpose other than structural integrity.

Fillet welds are defined by AWS as: "A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap or corner joint".

A fillet weld is shown in Figure No. 3. Section IX allows fillet welds to be qualified separately from groove welds for non-load-bearing applications. For load-bearing applications, a groove welding qualification is required because the groove welding qualification includes tensile testing.

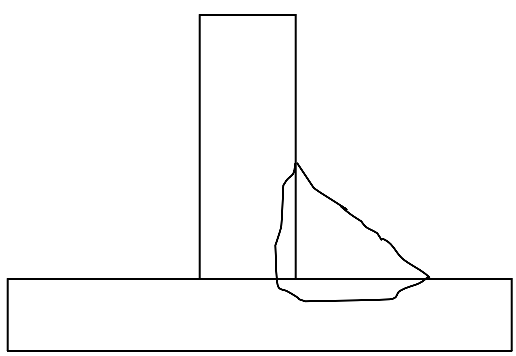


Figure No. 3

Fillet Weld

Groove welds are defined by AWS as: "A weld made in the grooves between two members to be joined".

Groove welds may very generally be pictured as those welds in which the weld metal is "within" the joint as opposed to fillet welds in which the weld metal is "outside" the joint. There are exceptions, however, such as a flare bevel weld which is considered a groove weld. A typical groove weld is shown in Figure No. 4. Groove welds might be further subdivided on the basis of whether they are full or partial penetration, backed or open root, double welded or single welded, etc.

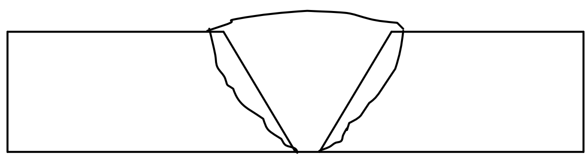


Figure No. 4

A Typical Groove Weld

Special Welds are seal welds, corrosion resistant overlay, hard facing, etc. These special welds serve some function other than strength and the Code specifies qualification tests which are consistent with the purpose of the weld. Take hard facing for an example. To qualify a hard facing welding procedure, Section IX requires hard facing a sample piece then, among other tests, taking hardness readings at various weld thicknesses. The procedure is qualified for the minimum thickness at which the hardness readings meet prespecified values.

The selection of joint/weld details is an interactive function of the designer, welding engineer, and production personnel. Certain phases of the selection however are weighed toward one or another of these people. The type of joint and type of weld is primarily the designer's responsibility, although input from the welding engineer and production personnel is usually necessary to assure a proper selection.

The type of joint and type of weld is determined by the welding process limitations and by the service requirements of the item. The ASME Code limits the type of joint and type of weld to selections proven safe for given conditions. For example, refer to Figure No. 5; this figure is taken from ASME Section VIII and shows the acceptable type of welds (i.e., various combinations of groove and/or fillet welds) which may be used for this particular construction. The type of joint, a T joint or Corner joint, is determined by the nature of the item. The designer must make the appropriate selection for type of weld within the restrictions of the Code.

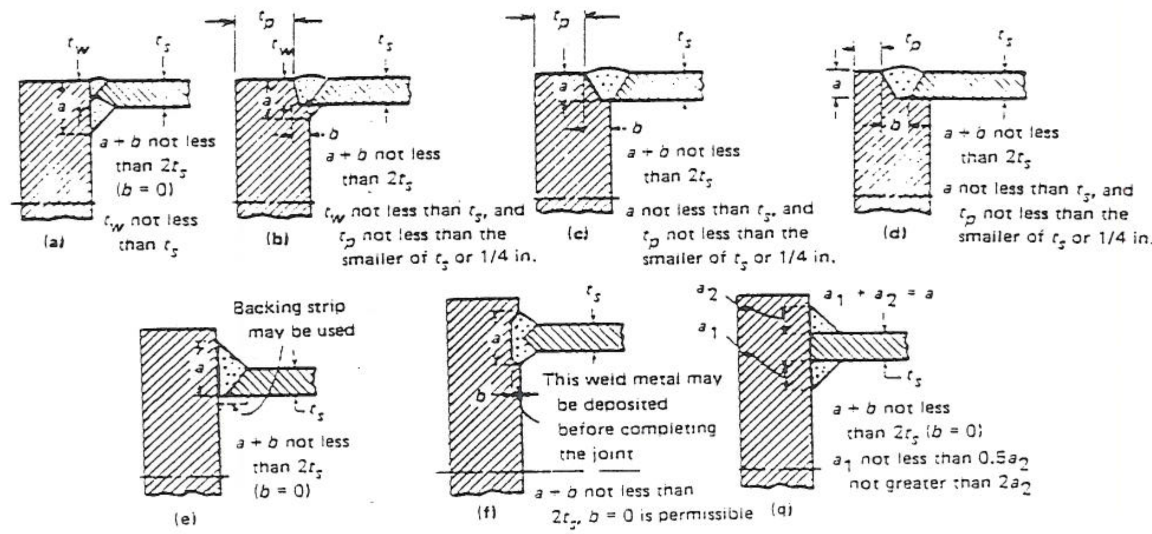


Figure No. 5

Various Types of Welds Permitted for T and Corner Joints

Once the type of joint and type of weld is determined, we must determine, within the constraints specified by the designer and/or Code, the geometric details of the weld. This determination is made considering such factors as accessibility, welding procedure, type of weld, restraint/distortion, and economics. Note that details of the groove are not specified in Figure No. 5. That is left to the Welding Engineer or production personnel. For example:

The bevel angle and type of groove (single bevel, vee, U, etc.) relate directly to the welder's ability to gain access to the weld and properly manipulate his equipment to avoid defects. A "T" joint in which the leg of the T is beveled as in Figure No. 6 would usually have about a 45° bevel instead of say a 22 1/2° bevel. Because of the restriction of the base of the T, the 22 1/2° bevel would not permit the welder sufficient access, a condition that may result in lack of fusion or incomplete penetration along the beveled surface. Restraint/distortion considerations however will also affect the weld geometry. A compromise may be necessary on bevel angle. A narrow bevel angle with less weld metal shrinkage results in less distortion, but decreased accessibility.

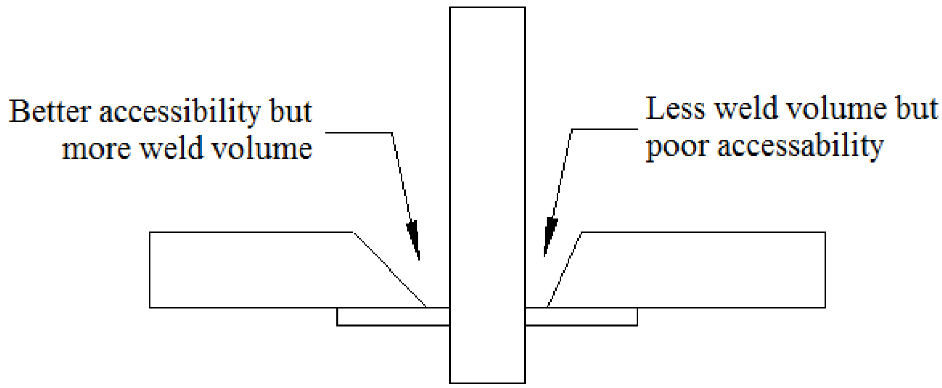


Figure No. 6

Example of Compromise Determining Weld Preparation Details

The desired welding process may restrict the weld geometric details for a variety of reasons. The type of weld or variation of type such as whether or not permanent backing strips are used will affect the weld geometry. Low hydrogen SMAW would not normally be used for an open root weld due to the extreme difficulty of obtaining sound weld metal on the back side of open root welds with the low hydrogen process.

Economics play a factor usually in the nature of attempting to reduce the volume of weld metal resulting in less filler metal to buy and less welder time required to deposit it. An example of reducing the volume of weld metal is shown in Figure No. 7. If a double V groove welded from both sides is practical, not only does it reduce distortion but saves the volume of weld metal represented by regions 3 and 4 shown in the Figure.

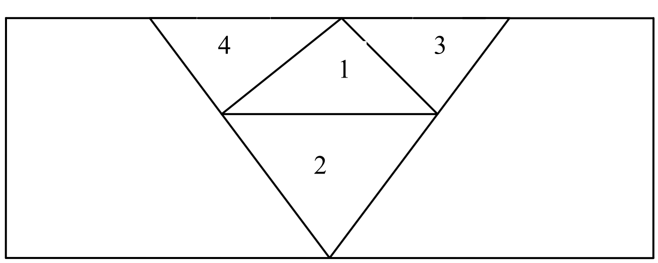


Figure No. 7

Using Joint Geometry to Reduce Volume of Weld Metal

4.0 Base Metal

Base metal properties such as strength, ductility, toughness, corrosion resistance, etc., may have an effect on and be affected by welding. Developing a welding procedure for every specific alloy would be a prohibitive paperwork task but, fortunately, it is unnecessary. Groups of alloys displaying similar weldability may be treated with a single welding procedure. ASME Section IX identifies these groups by "P" numbers ("P" for "Parent" material). "P" number groups identify materials of similar weldability, not exact weldability. There may be some variations, such as carbon content or tensile strength, within a P number grouping which will call for slight variations in welding technique.

"P" numbers are further subdivided into "Group" numbers. While P numbers are based on the spectrum of base metal weldability, Group numbers are based on the effects of welding on the material's toughness, i.e., susceptibility to brittle failure. If toughness is a concern, applicability of a welding procedure is limited not only to specific P number combinations but also to specific P number/Group number combinations. ASME Section IX welding P numbers are one or two digit numbers generated on the basis of the primary alloying element.

PI through P19 = Iron (Fe) base alloys

P2X = Aluminum (Al) base alloys

P3X = Copper (Cu) base alloys

P4X = Nickel (Ni) base alloys

P5X = Titanium (Ti) base alloys

P6X = Zirconium (Zr) base alloys

P7X = Cobalt (Co) base alloys

P1 carbon steels are generally defined as steels that contain up to .35% carbon, 0.6% silicon, and 1.65% manganese. When silicon or manganese exceeds these amounts the steel is called an alloy steel. Residual amounts of other alloying elements such as nickel, chromium and molybdenum are often found in carbon steels which were in the scrap used in making the steels. These elements must be controlled for carbon steels that are arc welded because their presence can cause problems. Limits on residual elements are defined in the ASTM/ASME material specifications.

P-2 materials are not listed in ASME Section IX. Historically, ASME used P2 for wrought iron, however wrought iron pressure vessels are no longer manufactured. The author is aware of one welding program that uses the P2 designation for cast irons. The primary weldablity problems with cast irons are excessive carbon and, in most cases, extremely low ductility.

P3, P4, P5A, P5B, and P5C materials are the low alloy carbon-molybdenum and chromium-molybdenum steels. P5A, P5B, and P5C materials were previously listed as just P5 material and the designation P5 is still seen on older WPSs. The principal distinction between welding these steels and welding carbon steels is the increased hardenability and therefore cracking susceptibility which occurs with increasing alloy content. You will notice increasing preheat and PWHT requirements in the Code for these steels as alloy content increases with P number. A guide for selecting preheat and PWHT is the carbon equivalent. Code requirements <u>must</u> be met. One well-known formula for carbon equivalent (CE) is:

$$CE=\%C+\frac{\%Mn}{6}+\frac{\%Ni}{15}+\frac{\%Cr}{6}+\frac{\%Mo}{4}+\frac{\%V}{5}$$

Steels having carbon equivalents by this formula of less than 0.40% usually require no preheating. Steels having a carbon equivalent of 0.40% to 0.60% usually require preheating. When the carbon equivalent by this formula exceeds 0.60%, it is usually necessary to use both preheating and postheating. It must be considered, however, that the carbon equivalent is based upon base metal composition and does not include other variables such as heat treated condition or degree of restraint. Therefore, at best, it is only an approximate measure of weldability and susceptibility to weld cracking.

P6 and P7 materials are those high alloy steels commonly known as martensitic (P6) and ferritic (P7) stainless steels. Whether a stainless steel is ferritic, martensitic or austenitic (austenitic stainless steels will be discussed later due to their special importance) depends on a complex interrelationship between composition and thermal history. We can only say the P6 materials are "predominantly" martensitic and the P7 materials are "predominantly" ferritic.

Cracking due to martensite formation is the primary welding concern with P6 materials. If enough carbon is present to increase the martensitic hardness, substantial preheats and retarded cooling is necessary. Embrittlement due to ferrite grain growth is the usual welding concern with P7 materials requiring heat input and maximum interpass temperature to be closely controlled.

P8 materials cover the austenitic chromium-nickel stainless steels. The standard grades of austenitic stainless steel recognized by the American Iron and Steel Institute (AISI) are listed in Table No. 1. A number of additional steels that represent modifications of the standard grades or proprietary compositions are also used in substantial amounts. Welding concerns with austenitic stainless steel include proper filler metal grade selection, heat input control to avoid distortion and sensitization, control of Delta Ferrite content to avoid hot cracking, and avoiding sigma phase embrittlement.

Table No. 1 Compositions of Standard Wrought Austenitic Stainless Steels				
Type	C	Cr	Ni	Other elements
201	0.15 max.	16.0–18.0	3.5-5.5	Mn 5.5-7.5, N 0.25 max.
202	0.15 max.	17.0-19.0	4.0-6.0	Mn 7.5-10.0, N 0.25 max.
205	0.15 max.	16.5-18.9	1.0-1.75	Mn 14.0-15.5, N 0.32-0.40, Mo 1.0-1.75
216	0.08 max.	19.75	6.0	Mn 8.25, N 0.37, Mo 2.5
301	0.15 max.	16.0–18.0	6.0-8.0	
302	0.15 max.	17.0-19.0	8.0-10.0	
302B	0.15 max.	17.0-19.0	8.0-10.0	Si 2.00-3.00
303	0.15 max.	17.0-19.0	8.0-10.0	S 0.15 min., P 0.20 max., Mo or Zr 0.60
303Se	0.15 max.	17.0-19.0	8.0-10.0	max.
304	0.08 max.	18.0-20.0	8.0-10.5	Se 0.15 min., P 0.20 max., S 0.06 max.
304L	0.03 max.	18.0-20.0	8.0-12.0	
305	0.12 max.	17.0-19.0	10.5-13.0	
308	0.08 max.	19.0-21.0	10.0-12.0	
309	0.20 max.	22.0-24.0	12.0-15.0	
309S	0.08 max.	22.0-24.0	12.0-15.0	
310	0.25 max.	24.0-26.0	19.0-22.0	
310S	0.08 max.	24.0-26.0	19.0-22.0	Si 1.50 max.
314	0.25 max.	23.0-26.0	19.0-22.0	Si 1.50 max.
316	0.08 max.	16.0–18.0	10.0-14.0	Si 1.50-3.00
316L	0.03 max.	16.0–18.0	10.0-14.0	Mo 2.00-3.00
317	0.08 max.	18.0-20.0	11.0-15.0	Mo 2.00-3.00
321	0.08 max.	17.0-19.0	9.0-12.0	Mo 3.00-4.00
347	0.08 max.	17.0-19.0	9.0-13.0	Ti is 5 x C (min.)
348	0.08 max.	17.0-19.0	9.0-13.0	Cb-Ta is 10 x C (min.)
384	0.08 max.	15.0-17.0	17.0-19.0	Cb-Ta is 10 x C (min.), Ta 0.10 max.
Manganese: 2.00 max. in all 300 types Silicon: 1.00 max. in all types except 302B, 310, 310S, and 314 Phosphorus: 0.060 max. in all 200 types, 0.045 max. in all 300 types except 303 and 303Se Sulfer: 0.030 max. in all types except 303 and 303Se				

P23 materials cover aluminum alloys in which the predominant alloying elements are magnesium and silicon. These are identified in the Aluminum Association system as 6xxx alloys (e.g. 6061). The primary welding considerations with these alloys are the rapid heat conduction from the weld area and overcoming the surface layer of aluminum oxide. Welding effects on the heat-treat or temper condition of the base metal may also be important.

P35 materials cover the aluminum bronze copper alloys. Alloys containing 7 to 10 percent aluminum are the most frequently welded.

P43 materials cover the group of nickel base alloys known generally as Inconel. Nickel base alloys find wide application where corrosion resistance and/or high service temperatures are a major concern. Hot cracking due to sulfur, halogen, or heavy metal (e.g. lead) contamination is a primary concern when welding these materials.

P51 material is titanium. Titanium is a highly reactive metal requiring a high level of care in shielding the hot base material from atmospheric oxygen and nitrogen. Auxiliary lead and trailing inert gas shielding is sometimes required. Welding for very sensitive applications is sometimes performed in an inerted chamber. From a practical standpoint, titanium can only be arc welded to itself.

Brazing P numbers are entirely different from welding P numbers. Since brazing does not melt the base material, the metallurgical interactions tend to be fewer and hence there are fewer P numbers. The distinctions among brazing P number are primarily made on the basis of surface interactions with brazing filler metal. Brazing P numbers are all three digit numbers (e.g. P101 is ferrous alloys with less than 0.90% chromium while P102 contains more than 0.90% chromium. P103 is cast iron and is found in braze welding procedures. P107 is copper alloys with less than 0.50% aluminum).

5.0 FILLER METAL

5.1 Designation and Nomenclature

The American Welding Society (AWS) publishes specifications for welding and brazing filler metals. The designations for these specifications take the form A5.X. For example, carbon steel covered electrodes are specified in A5.1. ASME has taken those filler metal specifications acceptable for use in boiler and pressure vessel fabrication and either identically or with minor changes published them in ASME Section II, Part C. The prefix "SF" is added to these selected filler metal specifications. For example, carbon steel covered electrodes for use in boiler and pressure vessel fabrication are covered by SFA5.1. In most cases, the A5.X and SFA5.X specifications are identical and this is stated in the SFA5.X specification.

The "AWS Classification" provides the specific filler metal(s) within the general specification. The classification systems vary with the individual requirements of different specifications. The classifications are usually based on some combination of chemical analysis, mechanical properties and electrode usability. The preferred AWS classification is listed on the WPS or BPS. Similar classifications which are also acceptable may be listed in the WPS or BPS notes.

This brings us to "F" numbers and, for ferrous materials, "A" numbers. Electrodes and welding and brazing rods are grouped by Section IX under "F" number designations (F for filler metal), which fundamentally indicate the ability of welders to make satisfactory welds or brazes with a given filler metal. Welding F numbers are found in Table QW-432 while brazing F-numbers are found in Table QB-432. Filler metal classification changes beyond the WPS or BPS options may be made within an F-number grouping with Welding Engineer concurrence. Also welders qualify for, among other variables, certain F number groupings. F-numbers might be considered as relating to filler metals as P numbers relate to base metals.

I hope you're not too confused now because there is one other item we must consider. There are twelve "A" numbers (A for analysis) for ferrous weld metals. "A" numbers are based on deposited weld metal analysis and play a similar role to F-numbers. Both the ASME Section IX rules for F-number and the rules for A number must be followed. "A" numbers play no role in performance qualifications or for brazing procedures. There are numerous exceptions to these F and A number rules but the WPS and BPS takes them into account.

The tungsten diameter and type is also listed for GTAW welding procedures.

A procedure should be prepared and followed for identification, storage, handling, issue and control of electrodes. Certain types of electrodes require special conditions during storage and handling for satisfactory service. For example, low hydrogen electrodes must be stored at elevated temperature to reduce the moisture content.

The Welding Supervisor is limited in the area of filler metal selection to using it as a criteria in selecting the WPS or BPS to assign a job. If certain filler metals not listed on an existing WPS or BPS appear desirable, the Welding Supervisor should contact the Welding Engineer. If the filler metal is appropriate, the Welding Engineer will either incorporate it into an existing procedure or prepare a new procedure as required. If permissible under Code rules, a specific filler metal not listed on a WPS or BPS may be used by identifying it on the Weld Traveler with Welding Engineer concurrence. An appropriate WPS or BPS is still specified and otherwise followed.

5.2 Filler Metal Selection Criteria

The "rule of thumb" in filler metal selection is to match the base metal chemical composition. However, the composition may be available in several forms even for the same process. The Welding Supervisor may need to determine whether to weld carbon steel with E7010 or E7018 using the SMAW process or ER70S-2 using the GTAW process. The decision in such cases will rest on factors other than filler metal type such as the type of weld or the base metal thickness. Consider the choice between EXX10 which are cellulose-coated electrodes and EXX18 which are low hydrogen coated electrodes. We do not use low hydrogen electrodes for the root of an open root joint. Also, cellulose coated electrodes are not used when there is danger of hydrogen cracking; such as with increasing base metal thickness and with increasing hardenability, i.e., increasing strength and alloy, including carbon, content.

Choosing a filler metal composition different from the base metal composition(s) may be dictated by service conditions for dissimilar base materials. For example, a groove weld is to be made between carbon steel and austenitic stainless steel. Carbon steel filler metal cannot be used because dilution with the austenitic stainless steel base metal would create a very hardenable alloy. Austenitic stainless steel filler metal could be used and would normally be the choice for service temperatures below about 800°F. Above these temperatures however, a problem appears because austenitic stainless steel has about 50% greater thermal expansion than carbon steel. Above about 800°F the difference in thermal expansion will begin to create excessive stresses at the carbon steel/stainless steel interface. See Figure No. 8a. The carbon steel's lower thermal expansion restricts the austenitic stainless steel's expansion and we have created what is known as a metallurgical notch, a condition in which stress concentrations are created not by geometric discontinuities but by an abrupt change in material properties.

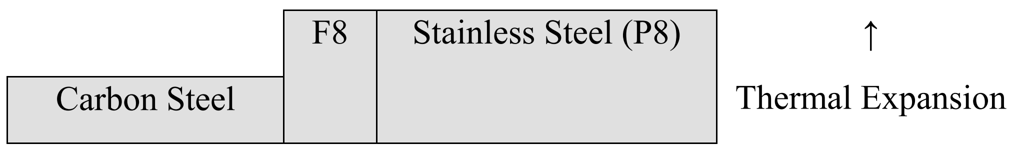


Figure No. 8a

Stainless Steel (P8) Expands More than Carbon Steel Creating Thermal Stress at the Carbon Steel/Stainless Steel Interface (F8 is Stainless Steel Weld Metal)

The solution to this problem is to use an Inconel (nickel based) filler metal. Inconel has a thermal expansion which is intermediate between carbon steel and austenitic stainless steel. By using Inconel filler metal, we accommodate the difference in thermal expansion between carbon steel and austenitic stainless steel by distributing it more or less equally between a carbon steel/lnconel interface and an Inconel/austenitic stainless steel interface as shown in Figure No. 8b..

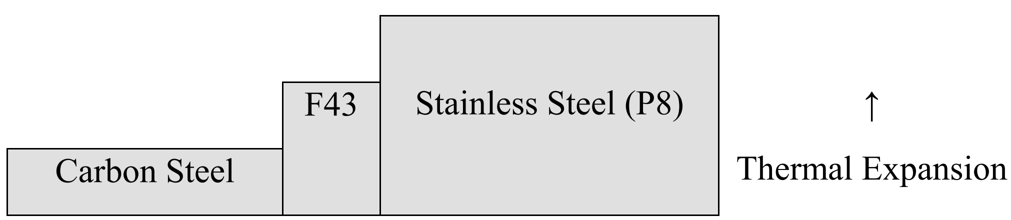


Figure No. 8b

Inconel (F43) Weld Metal Expansion is Intermediate to Carbon Steel and Stainless Steel. Thermal Stresses Still Exist but are Distributed Rather Than Localized.

Another example might be use of the braze welding process for cast iron. Cast iron filler materials are available but could result in an excessively hard weld. Braze welding incorporates a bronze filler material and is an excellent procedure for repair of cast iron. However, because the cast iron/bronze filler metal interface has potential for creating a galvanic cell, the procedure should not be used for applications in a corrosive environment such as seawater unless careful planning is made for corrosion protection.

When a filler metal with composition different from that of the base metal is used, the weld puddle will have a composition different from either the base metal or filler metal due to the intermixing (dilution) which occurs during welding. The weld puddle composition can be approximated using the base metal and filler metal composition and the anticipated weld penetration. See Figure No. 9. The Welding Engineer considers the properties of this hybrid composition when planning the WPS. An example of this would be using austenitic stainless steel filler metal on carbon steel base metal, e.g. for corrosion resistant cladding. Type 304/308 filler metal would dilute enough to create hard martensite or compromise the corrosion resistance. A better choice would be type 309 filler metal which has more chromium and nickel so the deposited weld metal, diluted with carbon steel, would still have a satisfactory composition.

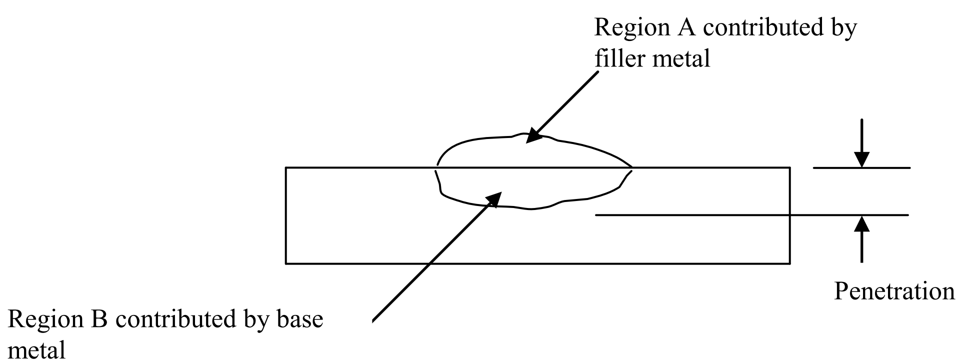


Figure No. 9

Weld Puddle Composition Dependent on Base Metal Composition and Weld Wire Composition Proportioned as Between Regions A and B

Filler metal selection is a major factor in the art/science of welding engineering. There are innumerable "tricks of the trade" and data available in the literature.

6.0 POSITION

A molten weld puddle is held by various forces such as gravity, surface tension, etc. acting on it. Depending on position, the effect of gravity may help or hinder. When gravity hinders, the puddle may sag or fall before it solidifies. This can cause undercut, overlap and excessive convexity. An example of sagging is shown in Figure No. 10.

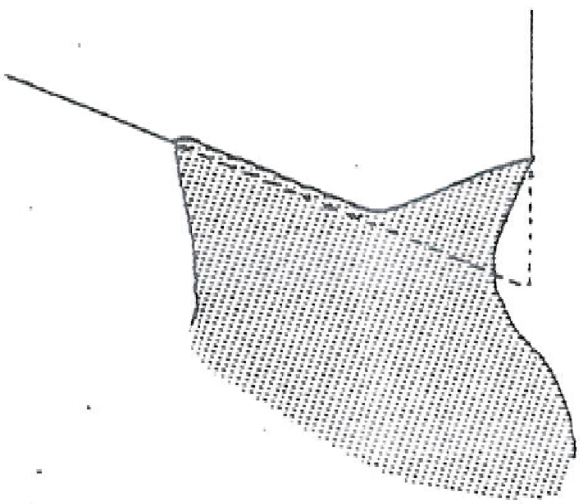


Figure No. 10

Low Spot/Undercut Due to Weld Metal Sag

With proper selection of parameters, e.g., a smaller puddle from a smaller diameter and/or cellulose coated electrode, controlling the effects of gravity becomes primarily dependent on the welder's ability to manipulate and control the puddle. The techniques for accomplishing this with various processes and positions are well documented in various "how-to-do-it texts". Mastering these techniques is a fundamental part of welder training. It is for this reason that position is usually a variable for performance qualification rather than procedure qualification.

Progression is applicable to welding in the vertical position and defines whether the weld is made from bottom-to-top of the joint (uphill) or from top-to-bottom (downhill) of the joint. The welding technique will differ and the WPS will state which progression to use.

Section IX has standardized welding and brazing positions for qualification. The groove weld positions in plate are shown in Figure No. 11. Brazing positions are functions of the direction in which the brazing filler metal must flow into the joint by capillary attraction. In brazing, as in welding, gravity can have an effect on the flow of the molten metal.

Flat (1G) Position

Vertical (3G) Position (Progression from top-to-bottom or bottom-to-top of picture)

Horizontal (2G) Position (Progression from front-to-rear or rear-to-front of picture)

Overhead (4G) Position

Figure No. 11

Plate Groove Welding Positions

7.0 PREHEAT AND INTERPASS

Preheat and interpass temperature refer to the temperature of the base metal(s) at the point of welding at the time welding is initiated (the arc is struck). Preheat temperature might more appropriately be referred to as "prewelding" temperature since the minimum temperature requirement always applies regardless of whether supplementary heat is required to obtain that temperature. Preheat temperature is a minimum temperature value. Interpass temperature is a maximum temperature value. The easiest way to picture this is to envision a temperature "window". The base metal at the point to be welded must be within this temperature "window" defined by minimum preheat and maximum interpass temperature each time a new welding pass is begun. The "window" obviously does not apply while the arc is running since the weld puddle is many times hotter than the maximum interpass temperature.

Some codes, such as ASME Section VIII, have recommended preheat temperatures. Others, such as ANSI B31.1 have required preheat temperatures. Preheat requirements are usually based on base metal mass, the "quench" mass, as opposed to PWHT requirements which are usually based on weld metal mass.

Preheats above ambient temperatures can serve a number of useful purposes such as reducing porosity, reducing weld shrinkage and shrinkage stress, reducing undesirable metallurgical structures, eliminating hydrogen cracking and overcoming thermal conductivity problems.

Porosity is the result of entrapped gases in the solidified weld puddle similar to entrapped bubbles in ice cubes. Precautions should always be taken to eliminate the source of the gases such as oil or grease contamination of the joint preparation. If porosity remains a problem, however, preheating may retard the weld puddle solidification sufficiently to permit these dissolved gases to escape.

Preheating reduces weld shrinkage. So long as ferritic weld metal is above the transformation temperature range, its yield strength is so low that it cannot exert a serious force on the joint. The overall joint does not shrink because contraction is accommodated by plastic flow of the weld metal. The plastic flow experienced by the weld metal is in the nature of hot working with no loss of ductility. From about 1300°F down, the shrinkage forces mount as the weld metal and heat affected base metal become stronger. The plastic flow is now cold work resulting in progressive loss of ductility.

Preheating, with a consequent reduction in cooling rate, may help to provide a favorable metallurgical structure in steel. The heat affected zone at the joint remains in the transformation temperature range for a longer period of time, which promotes the transformation of austenite to ferrite and pearlite or bainite instead of martensite. The preheated weld is less likely to have hard martensitic zones than a weld made without preheat. Preheating may reduce the cooling rate to such an extent that transformation is complete before the martensite starting temperature is reached.

If hydrogen cracking is a potential problem, the use of preheat will permit entrapped atomic hydrogen to diffuse from the weld area before cracking can develop. In critical situations it may be necessary to maintain or elevate the preheat for some time period after welding is completed to ensure that any dissolved hydrogen is given an opportunity to escape.

In some materials, e.g. copper and aluminum, the thermal conductivity is so high that heat supplied by the welding system is drawn away too rapidly for fusion to occur unless substantial preheats are used. Larger sections of pure copper may require as much as 1000°F preheat.

It should be cautioned that excessive preheat may sometimes be harmful. Quenched and tempered steels and HSLA steels may require the rapid cooling negated by preheat to maintain their properties. Some materials, e.g. ferritic stainless steels, may experience grain growth when slow cooled. Sensitization and distortion may occur if austenitic stainless steels are preheated.

The upper half of the welding "window", maximum interpass temperature, is frequently required to control metallurgical properties and/or distortion. The maximum heat may need to be limited to preserve properties in quenched and tempered steels and HSLA steels. In some materials, e.g. those not exhibiting a phase transformation such as ferritic stainless steels, excessive grain growth may occur if the material is allowed to become too warm. In austenitic stainless steels sensitization may occur. Also, because austenitic stainless steels have low thermal conductivity and high thermal expansion, the maximum interpass temperature must be controlled to avoid distortion. A maximum interpass temperature may sometimes be necessary to minimize distortion of machined surfaces.

When supplementary heat is required to obtain a preheat temperature, this heat is usually supplied either by an oxyacetylene torch or by resistance heating elements depending on whether the job is small and local preheat is suitable or if the job is large and more extensive preheat is required. Two precautions must be noted when using an oxyacetylene torch. "Hot spots" produced by holding the torch too long or close at a given spot may cause serious metallurgical damage. If the piece is large, thermal conductivity may draw the local preheat away surprisingly rapidly. The welder may obtain the required preheat and in the short time between extinguishing the torch and initiating the weld, the actual temperature in the weld area may have dropped well below the required temperature. Also, the desirable effects of preheat may be negated if the base metal mass at preheat temperatures is too small, i.e., the total "quantity" of heat is inadequate.

8.0 POST WELD HEAT TREATMENT

For a number of metallurgical reasons, it may be desirable to subject a completed weld to one of several post weld heat treatments before placing the weld in service. Examples might be normalizing of a graphitized material to redisolve the precipitated carbon, solution annealing of austenitic stainless steel to remove the effects of sensitization, and stress relief heat treatment to lower residual stresses resulting from weld shrinkage. Although these thermal cycles are referred to collectively as postweld heat treatment (PWHT) the vast majority of PWHT operations are stress relief operations. The WPS must be qualified for the specific type of PWHT. Most WPSs qualified with PWHT are qualified for stress relief below the lower critical temperature.

Residual elastic stresses exist to a degree in all completed weldments. In the gross item these stresses (tensile and compressive) necessarily balance to zero. However, in a given area the local stresses may be sufficient to inhibit the item's serviceability by increasing sensitivity to fatigue, stress corrosion cracking, etc. Residual stresses cannot exist above the yield point since by definition the material would plastically deform and relieve such stresses. However, stresses up to the yield point are quite common.

To relieve these stresses, we take advantage of the fact that the yield strength of a metal decreases with increasing temperature. If we heat the part to a suitable temperature, the residual stresses which existed at room temperature will be higher than the yield strength of the material at the higher temperature and the stresses will relieve themselves by plastic flow. We must be careful of two things however. We must not do metallurgical harm to the part by exceeding the transformation temperature or "critical" temperature. Also we must heat and cool the part uniformly or differential thermal expansion could cause more harm than good.

The various sections of the ASME Boiler and Pressure Vessel Code and the ANSI/ASME piping code specify the PWHT requirements for various conditions. The requirements for PWHT, as opposed to preheat, are generally based on the weld size rather than base metal size since residual stresses are usually proportional to weld size.

The temperature reached during the stress relief treatment has a far greater effect in relieving stresses than the length of time the specimen is held at that temperature. The relief attributable to time-at-temperature is due to a second mechanism (creep). The closer the temperature is to the critical temperature, the more effective it is in removal of residual stresses.

There are specialized half-bead/temperbead procedures that may be used when PWHT is impractical. These procedures have very strict code rules covering their use. Carefully prepared procedures should provide generic instructions for application of the temper bead technique. The temperbead technique is described in section 11, Technique.

9.0 SHIELDING GAS

Environmental gases dissolved in the weld puddle may cause such problems as porosity, cracking and embrittlement. The weld puddle must be protected from these gases. In many cases the solidified weld metal and base metal must also be protected until they are below a safe temperature. Cleaning of the weld preparation and/or chemically active fluxes take care of most gases originating from surface contamination, but protection from atmospheric gases is still essential.

There are two methods for accomplishing this. A liquid flux originating from the electrode coating (SMAW) or core (FCAW) will, among other functions, exclude atmospheric gases. The other method of excluding atmospheric gases is to flood the weld area with a "neutral" gas or gases. What constitutes a "neutral" gas may vary with a given situation. This shielding gas may sometimes be CO_2 resulting from the chemical breakdown of the coating on cellulose type electrodes or the core material of certain FCAW electrodes. This section however centers on the technology of independently supplied shielding gases.

When including mixtures of the various shielding gases, there are a very large number available. Some common gases or mixtures include oxygen/acetylene, argon, 75 % argon/25% carbon dioxide, and 75 % argon/25 % helium. Oxygen/acetylene are the gases used in oxyacetylene welding. Oxygen and acetylene combine to form water vapor, carbon dioxide and heat. The heat is used for melting the base metal and filler metal. The carbon dioxide, as it does when resulting from decomposition of a cellulose electrode covering or from an external supply system, provides shielding for the weld puddle.

Argon is the inert gas used for the majority of GTAW procedures. Some characteristics of argon are easy arc initiation, a stable arc and lower arc voltage at given current values and arc length. Argon is heavier than air and will settle to the bottom of an enclosure. When purging, a vent must be provided at high point(s) to preclude trapping of air pockets in the weld area.

The mixture 75% argon/25% carbon dioxide is used in some FCAW procedures.

Helium provides better shielding in the overhead position since it is less dense than air and therefore rises.

The WPS will specify the type and composition of auxiliary shielding gas along with the flow rates. Frequently, there must be some shielding gas flow prior to arc initiation to purge the equipment and after extinguishing the arc to protect the still-hot weld puddle.

In more sensitive materials, such as austenitic stainless steels, the shielding gas flowing over from the welding surface must be supplemented if the back side of the weld bead is exposed to the atmosphere such as in an open root joint. This is frequently referred to as back purging or purging. Purging must usually be maintained for some specified thickness since heat from subsequent weld layers can reheat the root bead sufficiently for harm to be caused by atmospheric gases even though the root bead is already fused.

The many factors involved in shielding a weld puddle with auxiliary shielding gases may be more easily understood by remembering one point. Atmospheric gases must be excluded from the liquid and, to a safe temperature, the still-hot-but-fused weld puddle. Drafts which may blow the shielding away must be avoided. Extra consideration must be given exposed surfaces where the gas may not be confined as easily as within a deep groove. There must be sufficient gas flow, although excessive flow may cause turbulence which entrains air and defeats the purpose. Gas lens may help if this is a problem. The supply system must be monitored to assure air and/or moisture is not drawn into cracked hoses or loose fittings. Also, contaminated cylinders are rare, but they do occur.

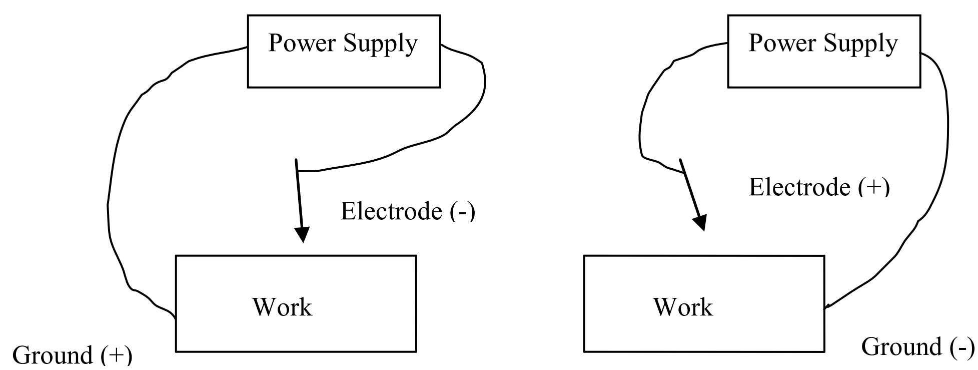
10.0 ELECTRICAL CHARACTERISTICS

Electrical characteristics consist of a description of the values and interrelationship of current, voltage, and time. Changes in these patterns for a given process, filler metal etc. can have a profound effect on weld bead size, shape, and heat input.

There are two types of current used in welding. In direct current (DC) the electron (current) flow is in one direction only (Figure No. 12). Direct current is further subdivided by the direction in which the current flows (the polarity), from the electrode to the work or vice versa. In alternating current (AC) the current flow changes direction in time in a regular repeating pattern.

The terms Direct Current Straight Polarity (DCSP) and Direct Current Reverse Polarity (DCRP) are older terms still found quite often. The preferred terms are the more descriptive Direct Current Electrode Negative (DCEN) and Direct Current Electrode

Positive (DCEP). A memory aid is that the District of Columbia (DC) is home to the House of Representatives (REP is reverse electrode positive) and the Senate (SEN is straight electrode negative).



Electrode Negative (DCSP) Electrode Positive (DCRP)

Figure No. 12

Direct Current Polarity

While current, regardless of type, is a measure of electrical flow, voltage is a measure of the "force" behind that flow. In general, increasing voltage will increase the width and decrease the penetration of a weld bead. The manner in which voltage varies with current is especially important in manual GTAW and SMAW. For these processes power supplies known as constant current (as opposed to constant voltage) are used. In constant current machines the change in current is relatively small for large changes in voltage. With subtle changes in arc length with these manual processes the arc voltage will vary. However, the current will not vary significantly permitting the operator to more freely manipulate the electrode.

Other processes, such as FCAW and GMAW, require a constant voltage power supply. Voltage changes become a means of monitoring the arc length so the melt-off rate of the electrode can automatically adjust. Otherwise the electrode may melt back into the electrical contact or plunge into the puddle. When constant current machines are used for these processes, a separate voltage-sensing device is required to continually adjust the wire feed rate.

Current and voltage may be made to vary with time, as in AC current. Pulsed current is a technique used in DC welding and means that at predetermined intervals the current is made to vary from a low (background) level to a higher (peak) level although the polarity does not change as it does in AC. Pulsed current is useful where weld puddle control is a problem such as in open root welds or out-of-position welds. In pulsed GTAW, the electrode motion is coordinated with the pulse rate so pulses occur at the joint edges when filler metal is added. Pulsed GMAW is used to gain the advantages of spray transfer in out-of-position welds. The puddle is smaller and control is easier. Arc timing is an important factor in such finite sequences as stud welding.

The combined effect of electrical characteristics is quite significant and varies with process, filler material, base metal, equipment, etc. In SMAW direct current as opposed to alternating current:

1. Is better at low currents and with small diameter electrodes.
2. May be used for all classes of covered electrodes with satisfactory results.
3. Exhibits generally easier arc starting.
4. Makes maintaining a short arc easier.
5. Produces less weld spatter.

While alternating current as opposed to direct current:

1. Rarely causes an arc blow problem.
2. Is well suited for the welding of thick sections using large diameter electrodes.

In GTAW the effects of current are a little different. When DCEN is used electrons pass through the arc to bombard the base plate. This causes nearly 70% of the arc heat to accumulate in the base metal to assist fusion and penetration. When DCEP is used a cleaning effect is created on the surface of the base metal. While an electrode positive connection furnishes a cleaning effect, it also heats the tungsten electrode. The electrode may get hot enough to melt, transfer to the weld pool, and contaminate the base metal. Alternating current offers the advantage of both DCEN and DCEP.

Maximum heat input is important for certain base materials such as quenched and tempered steel, when special care must be taken to control the base metal HAZ and weld metal structure, or when distortion control is a problem.

To determine the heat input, multiply voltage, (related to force) by current (related to flow). Finally, dividing by the travel speed gives heat per unit length. The factor 60 is a unit conversion. The formula is:

$$HI = \frac{V \times A \times 60}{TS} = \text{Joules/inch}$$

HI = heat input

V = arc voltage

A = Amperes

TS = Travel speed in inches/minute

In many welding processes such as SMAW and FCAW the specific coating may contain ionizing material which makes certain electrodes more suitable on one type of current than another.

One characteristic of DC arc welding, not usually found when using AC arc welding, is the occasional arc instability known as arc blow. This action is due to the magnetic field built up around the arc. A magnetic field exists around all current carrying conductors. Normally this field is not a problem but when "bunched" such as in a corner, it can cause unwanted deflection of the arc. This effect may also be caused by magnetized base material. Arc blow, when carefully controlled, has at times even proven useful.

11.0 TECHNIQUE

“Technique" covers a variety of items not specifically covered under the other variables such as manipulation of the electrode, sequence of operations, cleaning methods, special equipment, etc. Manipulation of the electrode includes use of the weave or stinger bead technique. If weave bead technique, it includes the pattern of the weave. Weave patterns of different contours are used to control the weld puddle under various conditions of position, process, progression, etc. It is important in overcoming the effects of gravity in out-of-position welding, assuring adequate tie-in on the sides of grooves, controlling heat input in sensitive conditions, and other purposes. Proper manipulation of the electrode, including weave pattern and angle of approach can make the difference between a satisfactory weld and an unsatisfactory weld.

Sequence of operations includes placement of weld beads in multiple pass welds, backwelding, sequencing of bead placement etc. It even includes whether single or multiple pass welds are used. Placement of weld beads may have an effect on fusion, slag inclusion, weldment distortion and any number of other considerations. Backwelding is a sequence in which a groove weld is made by welding from both sides of the groove with welding from the second side usually preceded by grinding or gouging the root of the first side.

Sequencing of bead placement including sequencing of welds may have a significant effect on distortion, cracking and/or residual stresses.

An example of sequence of operations would be use of the temper bead technique shown in Figure No. 13. This technique, by careful sequencing of operations and bead placement, assures HAZ refinement negating the need for PWHT. This is accomplished in conjunction with other variables such as preheat and filler metal selection. The HAZ of the second layer penetrates through the HAZ associated with the first layer. By controlling the heat input and therefore the penetration of the second layer, the extent of the HAZ overlap may be controlled. Proper control of penetration will result in the optimum condition of a fine grained structure throughout the weld. The temperbead technique may be continued until all course grained regions are above the original base material surface. The weld may then be dressed to the original surface.

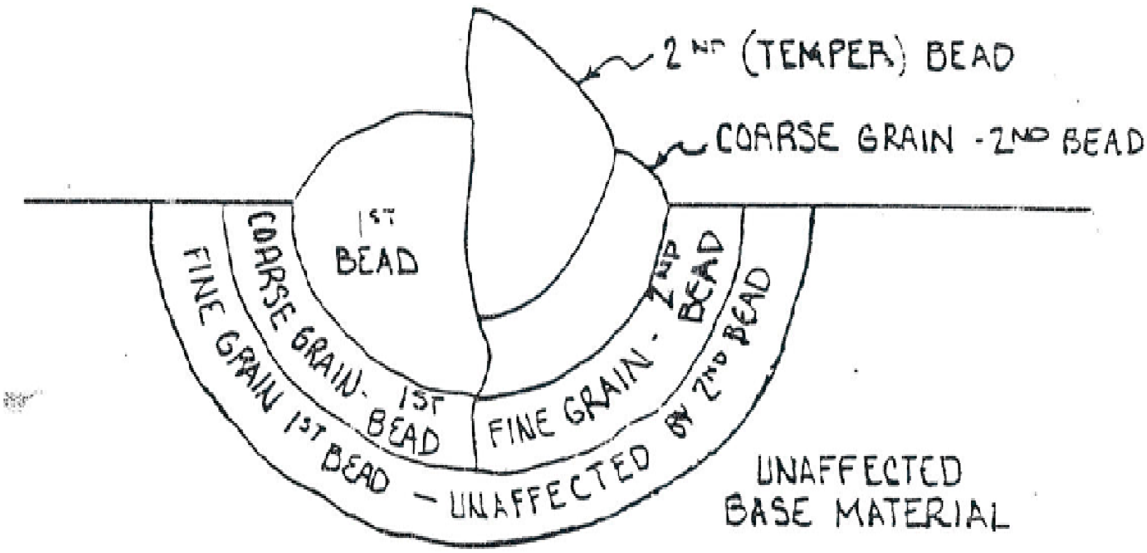


Figure No. 13

Principle of the Temperbead Technique

Cleaning methods include both cleaning of the weld preparation prior to welding and cleaning between passes of multi-pass welds. It usually includes such methods as wiping, solvents, wire brushing, grinding, etc. While cleaning may sound somewhat like a mundane operation, failure to perform it properly may result in such problems as gross porosity or cracking. Improper cleaning is frequently the cause of many welding problems.

Equipment is sometimes considered a welding "technique". Arc stud welding requires special equipment. FCAW requires constant voltage power supplies. Nozzle or cup size is relevant in FCAW and GTAW.

Another technique is weld metal peening. This operation, consisting of striking the weld metal to work it, is frequently used for distortion control by counteracting the weld metal shrinkage. Caution must be exercised not to overwork the weld metal causing rupture. Also the last pass and usually the first must not be peened. Peening the first pass could punch through the weld metal or cause cracking unless the groove is backed by substantial base material. Peening the last pass would result in cold worked metal not refined by subsequent weld beads unless the weld is PWHT.

Technique in brazing could include such things as pre- and post-cleaning of the braze joint and method of feeding the brazing filler metal such as preplaced material or face feeding.