PDH Course S150

Structural Steel Welding

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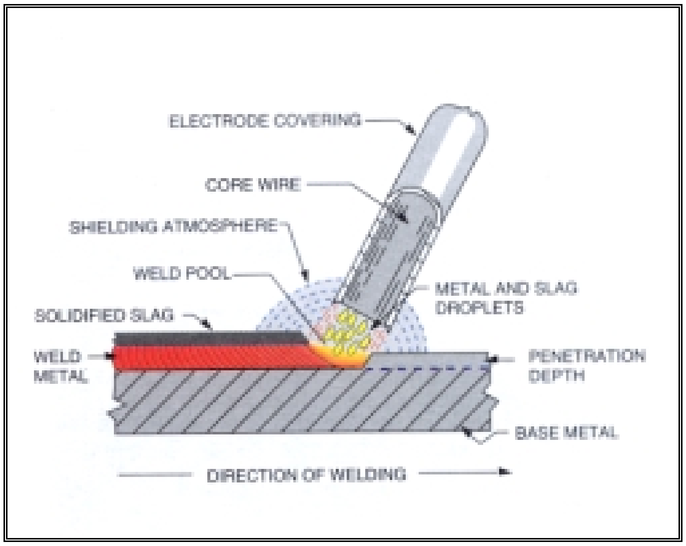
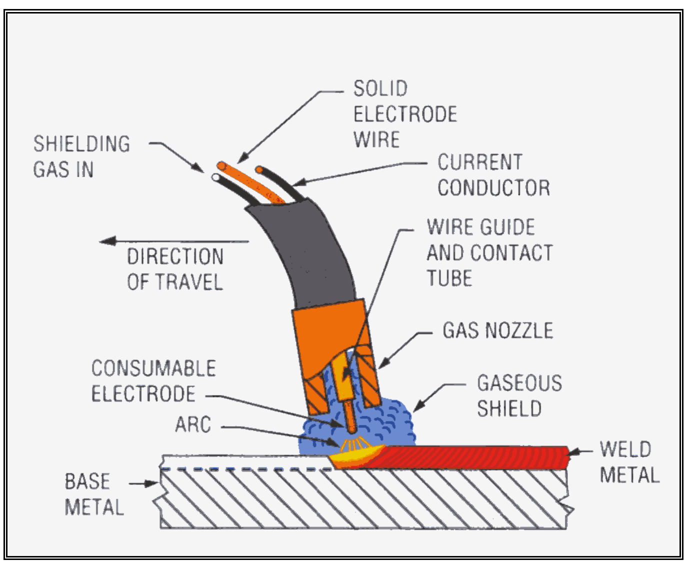
Arc welding requires striking a low-voltage, high-current arc between an electrode and the workpiece (base metal). The intense heat generated with this arc melts the base metal and allows the joining of two components. The characteristic of the metal that is being welded and the joint type (i.e. groove, fillet, etc.) dictates the welding parameters and the procedure that needs to be followed to obtain a sound weld joint.

Typical Arc Welding Processes:

Shielded metal arc welding (SMAW): Shielded metal arc welding, which is also known as stick welding, is the most widely used process. The arc is struck between the metal to be welded and a flux coated consumable electrode. The fluxes are mostly made from mineral components and cover the hot weld deposit and protect it from the environment. The solidified glassy product, slag should be removed by chipping or with a wire brush.

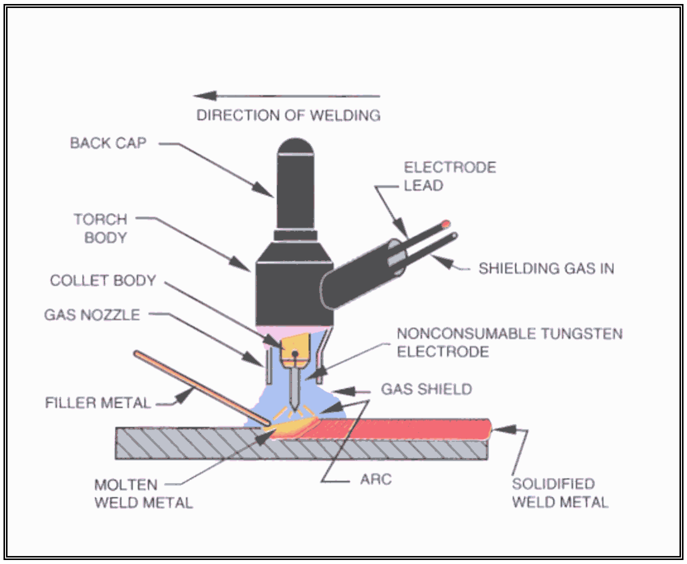


Gas metal arc welding (GMAW): This process is also referred to as metal inert-gas (MIG) welding uses an uncoated continuous wire. The weld area is shielded from contamination by the gas that is fed through the welding torch. The mode of metal transfer (spray, globular, short-circuiting, pulsed-arc) is varied by adjusting the amperage and the shielding gases used depending on the welding position and the type of joint.



Flux-cored arc welding (FCAW): The shielding gases and slag are provided by the decomposing flux that is contained within the electrode. Auxiliary shielding is also used in certain instances where deeper penetration is needed.

Gas tungsten arc welding (GTAW): Also known as tungsten inert-gas (TIG), the process uses a non-consumable electrode. The shielding gas is again fed through the welding torch. Welding may be accomplished without the addition of filler metal, which is advantageous especially for thin walled parts.



Shielding gases:

The primary purpose of the shielding gas is to protect the molten weld from contamination and high temperature oxidation by the surrounding atmosphere. Although plain inert gases may not be suitable for all applications, mixtures with reactive gases (i.e. oxygen, nitrogen, hydrogen and carbon dioxide) in controlled quantities will produce stable and relatively spatter-free metal transfer.

Argon: Argon by itself is frequently used for MIG welding of nonferrous metals. A mixture of argon and oxygen or argon and carbon dioxide is usually preferred for ferrous metals. The high-density arc that is created by argon permits the energy to go into the work piece as heat resulting in a narrow bead width with deep penetration.

Helium: has higher thermal conductivity and arc voltage than argon, which causes it to produce broader weld beads. Because helium is a very light gas, higher flow rates must be used for effective shielding. This characteristic is beneficial in overhead welding.

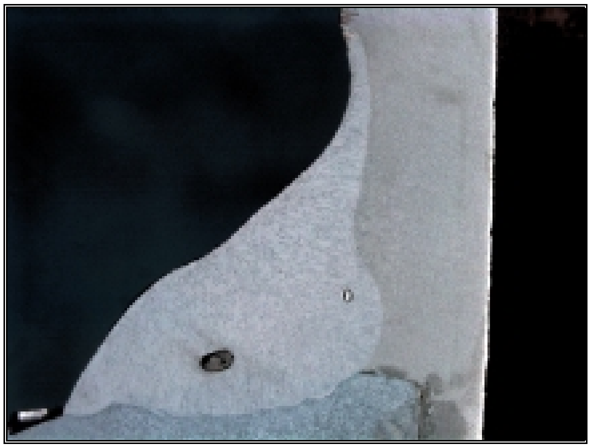
Carbon dioxide: is widely used for steels. Higher welding speed, better joint penetration and sound deposits with good mechanical properties can be achieved. Carbon dioxide is not an inert gas as the argon and helium and breaks down into carbon monoxide and free oxygen under the heat of the arc. The oxygen is used to superheat the weld metal transferring across the arc.

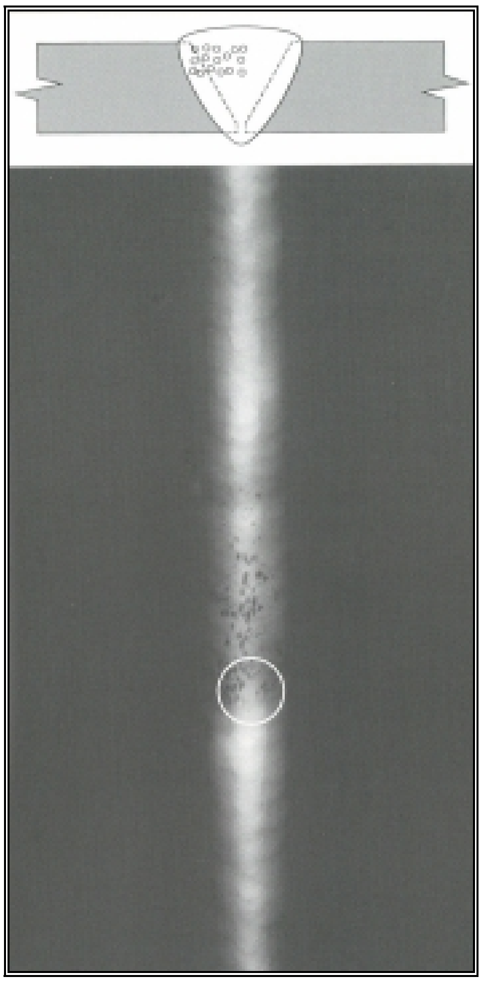
Arc welding defects:

Most welds contain defects (porosity, cracks, slag inclusions, etc.). The question is to determine if they are significant considering the application. Typically, the applicable codes or standards specify the maximum allowable limits of these types of defects in a weld based on the application. Sometimes discontinuities that may not affect mechanical properties may reduce corrosion performance. The properties of the heat-affected zone (HAZ) are one of the significant factors to consider when evaluating the soundness of the weld joint. The HAZ may be considered as a discontinuity because of the metallurgical alterations as a result of the welding heat, which causes very rapid heating and cooling rates. Grain growth, phase transformations (i.e. brittle untempered martensite which can form depending on the cooling rate and the chemical composition of the base material), formation of precipitates or overaging (loss of strength in precipitation-hardened alloys) all has a drastic effect on the properties of the HAZ. It is possible to improve the weld zone properties by controlling the cooling rate. This may be accomplished by slowing the cooling rate down either by increasing the heat input or preheating (i.e. heating the metal up before welding).

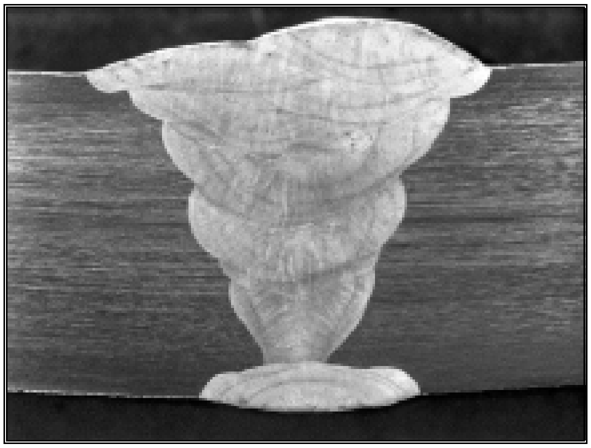
Porosity: Gas pockets are formed in the weld metal when they are entrapped during solidification. Molten steel readily absorbs hydrogen, carbon monoxide and other gases to which it is exposed. Since these are not soluble in solid metal, they are expelled as the metal solidifies. Standard shielded arc electrodes with organic coating such as E6010 produce an atmosphere around the arc that contains hydrogen, a notable contributor to porosity. When using such electrodes, welding should be done slowly to allow the gases time to escape since too high of a travel speed causes rapid solidification of the weld metal leading to porosity. Weld joint cleanliness is also crucial in avoiding porosity since moisture, oil, paint, or rust on the base metal may also cause porosity by introducing oxygen or hydrogen into the weld metal. Employing some minimum preheat temperature is often useful to remove condensation. It is also necessary to maintain the fluxes and the coated electrodes dry to avoid moisture pick-up. They are typically kept in an oven at approximately 250ºF, or if the hermetic seal is broken on the containers then the consumables (e.g. welding rods) should be baked at higher temperatures to drive off the moisture and restore the low hydrogen characteristics. Common causes and remedies of porosity are listed below along with a macrograph of a fillet weld containing porosity. An illustration of a groove weld which exhibits cluster porosity is also included with its corresponding radiograph.

Porosity: gas pockets or voids that are found in welds	
Causes	**Remedies**
Excessive hydrogen, nitrogen or oxygen in welding atmosphere	Use low hydrogen welding process, 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 clean wire and store fillers in a clean area
Improper arc length, welding current or electrode manipulation	Modify welding parameters and techniques
Volatilization of zinc from brass	Use copper-silicon filler, reduce heat input
Porosity: gas pockets or voids that are found in welds	
Causes	**Remedies**
Galvanized Steel	Use E7010 electrode and manipulate the arc heat to volatilize the galvanizing (zinc) ahead of the molten weld pool
Excessive moisture in electrode covering or on joint surfaces	Use recommended procedures for baking and storing electrodes
High sulfur base metal	Use electrodes with basic slagging reactions

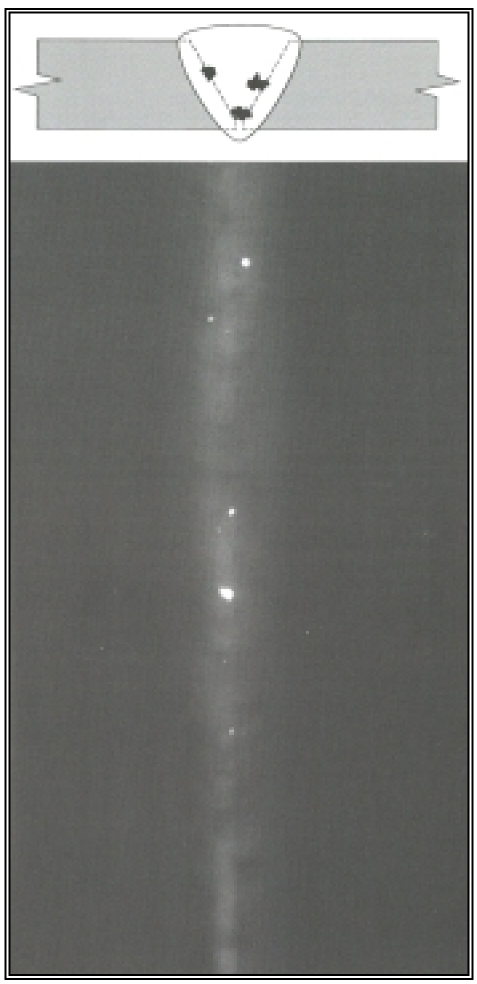




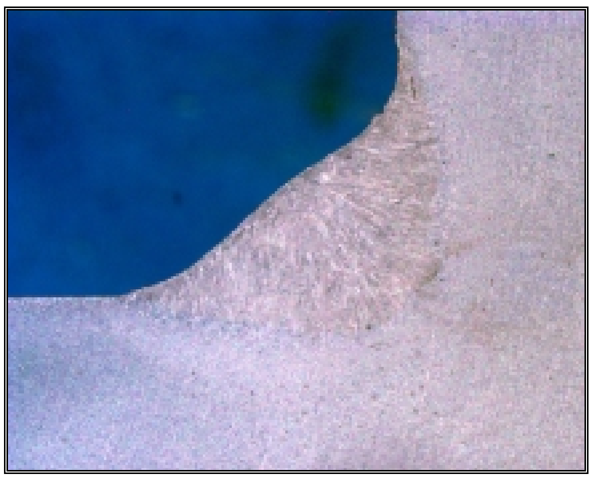
Slag inclusions: The oxides or other nonmetallic inclusions that become entrapped in the weld metal. They may be caused by contamination or inadequate cleaning between weld passes. The slag derived from fluxes employed during welding needs to be cleaned between weld passes (in multi-pass operations) using a chipping hammer or a wire brush. The macrograph below illustrates a successful multipass weld joint.

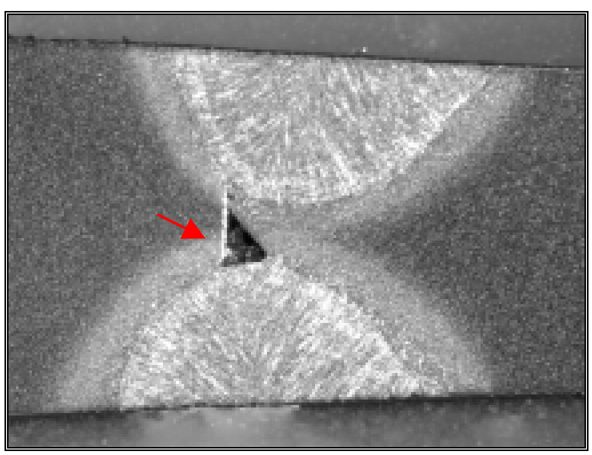


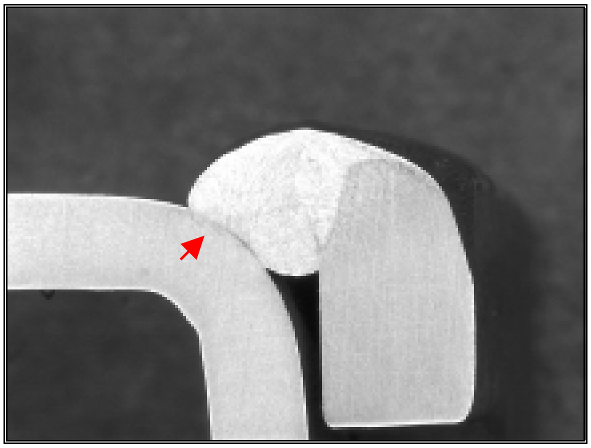
Tungsten inclusions: In the TIG process, the touching of the electrode to the weld metal may cause transfer of the tungsten particles into the weld metal. These inclusions are detected by x-ray and show up as bright particles since they are much denser than the steel. An example is shown below where the x-ray revealed the tungsten inclusions.



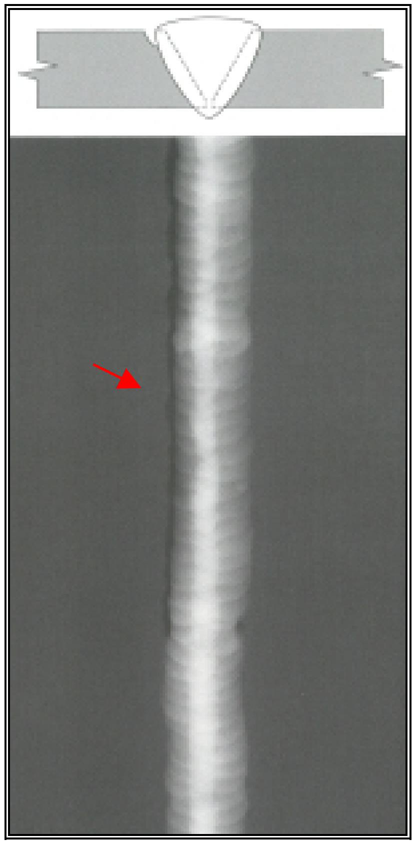
Incomplete fusion/penetration: Although these terms are sometimes used interchangeably, lack of fusion occurs when the weld and base metal fail to adequately fuse together. It can also be encountered between weld passes. It may be caused by not raising the temperature of the base metal or previously applied weld metal to the melting point or failure to remove the slag or mill scale. Lack of penetration is typically due to inadequate heat input for the particular joint that is being welded and is usually seen at the sidewalls of a weld joint, between weld passes or at the root of the weld joint. The shielding gas can also influence the penetration; typically helium is added for nonferrous metals and carbon dioxide is added for ferrous metals (to argon) to increase penetration. The first macrograph below shows an acceptable single pass fillet weld profile with adequate base metal penetration and root fusion. The second macrograph shows lack of penetration to the root in a double welded joint, and the third macrograph illustrates lack of penetration to one of the members. The final illustration shows the sketch of another variation of incomplete root penetration and its appearance on an x-ray film (radiograph).

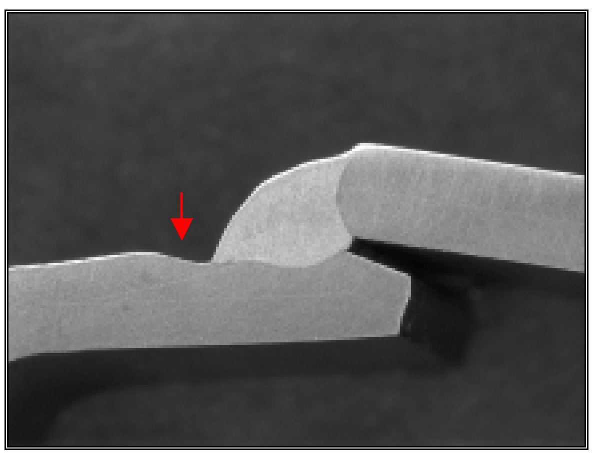




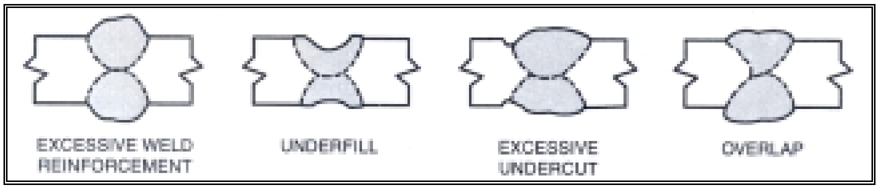


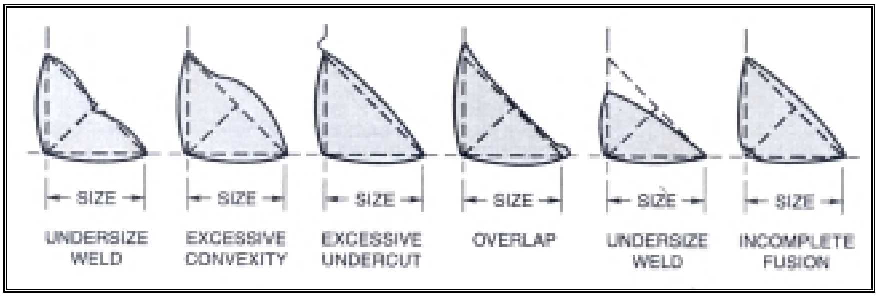
Undercut: This occurs when a groove that is formed adjacent to the weld as a result of the melting of the base metal remains unfilled. An example is shown in the macrograph below (at the toe of the fillet weld) along with the appearance of this type of defect on a radiograph of a groove weld.





Weld profile: The profile of a finished weld may have a considerable effect on the performance under dynamic loading conditions. Overlap, excessive reinforcement or mismatch can provide stress concentration points where fatigue cracks can initiate. Typical unacceptable butt and fillet weld profiles are shown below along with an example of poor fit-up (mismatch):





Macrograph showing poor fit-up (butt weld)

Arc strikes: They are caused by the unintentional melting of the base metal outside the weld deposit area by the welding arc. It can create localized hard or soft spots, cracking or undercut. Another welder-induced defect is weld spatter. It usually occurs when excessive welding current, long arc or welding voltage is used. Below macrograph shows arc strikes near a fillet weld.

Cracks: Cracks are the most serious type of weld defects that can lead to catastrophic failures in service. There are many different types of cracks. One way of categorizing them is as surface or subsurface cracks. Another way would be as hot (which occur during or immediately after the weld is made) or cold (cracks that occur after the weld has cooled to room temperature-sometimes within hours or days). In general, weld or heat- affected zone cracks indicate that the weld or the base metal has low ductility and that there is high joint restraint. Many factors can contribute to this condition such as rapid cooling, high alloy composition, insufficient heat input, poor joint preparation, incorrect electrode type, insufficient weld size or lack of preheat. Some common causes and remedies are given in table below.

Cracks: Hot and cold cracks or microfissures can form in the weld or the base metal	
Causes	**Remedies**
Highly rigid joint	Preheat Relieve residual stresses mechanically Minimize shrinkage stresses using backstep sequence (a longitudinal sequence in which weld passes are made in the direction opposite to the progress of welding)
Excessive dilution (change in chemical composition of a weld deposit caused by the admixture of the base metal)	Change welding current and travel speed Weld with covered electrode negative; butter the joint faces prior to welding (buttering is depositing surfacing metal to provide metallurgically compatible weld metal to the subsequent weld passes)
Poor fit-up	Reduce root opening
Small weld bead	Increase electrode size, raise welding current, reduce travel speed
High sulfur base metal	Use filler metal low in sulfur
Excessive distortion	Change to balanced welding on both sides of joint
Crater cracking	Fill crater before extinguishing the arc
High residual stresses	Redesign weldment, change welding sequence, apply intermediate stress relief
High hardenability	Preheat, increase heat input, heat treat without cooling to room temperature

Photograph illustrating crater cracking resulting from abrupt weld termination in an aluminum weld (MIG process)

The effect of carbon equivalent:

The carbon equivalent (C.E.) may be considered as the main factor in estimating preheat need. Generally, the higher the carbon content of a steel, the greater the tendency to form a hard and brittle HAZ. This necessitates the use of preheat and low hydrogen electrodes. Carbon, however, is not the only element that influences hardenability. Other elements in steel also are responsible for the hardening and loss of ductility that occur with rapid cooling. One of the various empirical formulas used to determine carbon equivalent is given in the Structural Steel Welding Code (AWS D1.1) as follows:

$$\%C.E. = \%C + \%(Mn+Si)/6 + \%(Cr+Mo+V)/5 + \%(Ni+Cu)/15$$

The approximate recommended preheat temperatures based on C.E. are:

For up to 0.45%………..preheat is optional

0.45-0.60%………………200-400ºF

Over 0.60%……………....400-700ºF

Usually a steel that requires preheating must also be kept at this temperature between weld passes. The heat input of the welding process is adequate to maintain the required interpass temperature on most weldments. On massive components this may not be the case and torch heating between passes may be required. Since the purpose of preheating is to reduce the quench rate, the same slow cooling rate must be accomplished for all passes.

Besides the widely used carbon equivalent criteria, the following factors should also be considered when determining the need for preheat/post weld heat treat: code requirements, section thickness, restraint, ambient temperature, filler metal hydrogen content and previous cracking problems.

AWS Classifications:

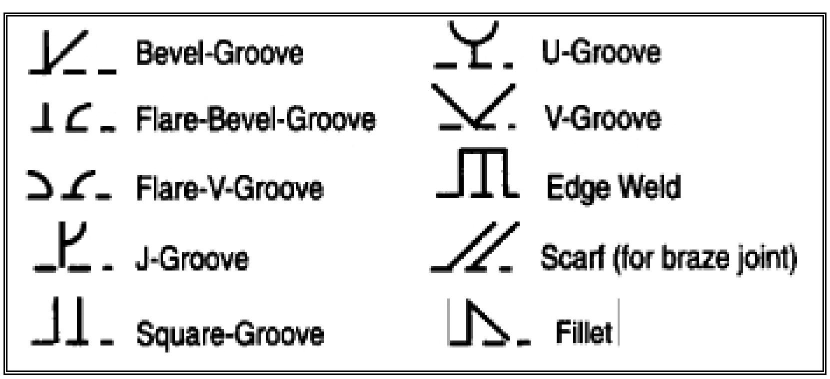
The American Welding Society numbering system tells a lot about the properties and usability of the electrode. Using the stick electrode numbering system as a representative example:

The prefix "E" designates an arc-welding electrode. The first two digits of a four-digit number and the first three digits of a five-digit number indicate tensile strength. For example, E7018 is a 70,000-psi tensile strength electrode while E10018 designates a 100,000-psi one.

The next to last digit indicates the position. 1 is for all position, 2 is for flat and horizontal and 3 is for flat, horizontal, vertical down and overhead. The last two digits together indicate the type of electrode coating and the correct polarity to use. An example would be "18" for iron powder, low hydrogen with AC or DC+.

Weld Symbols:

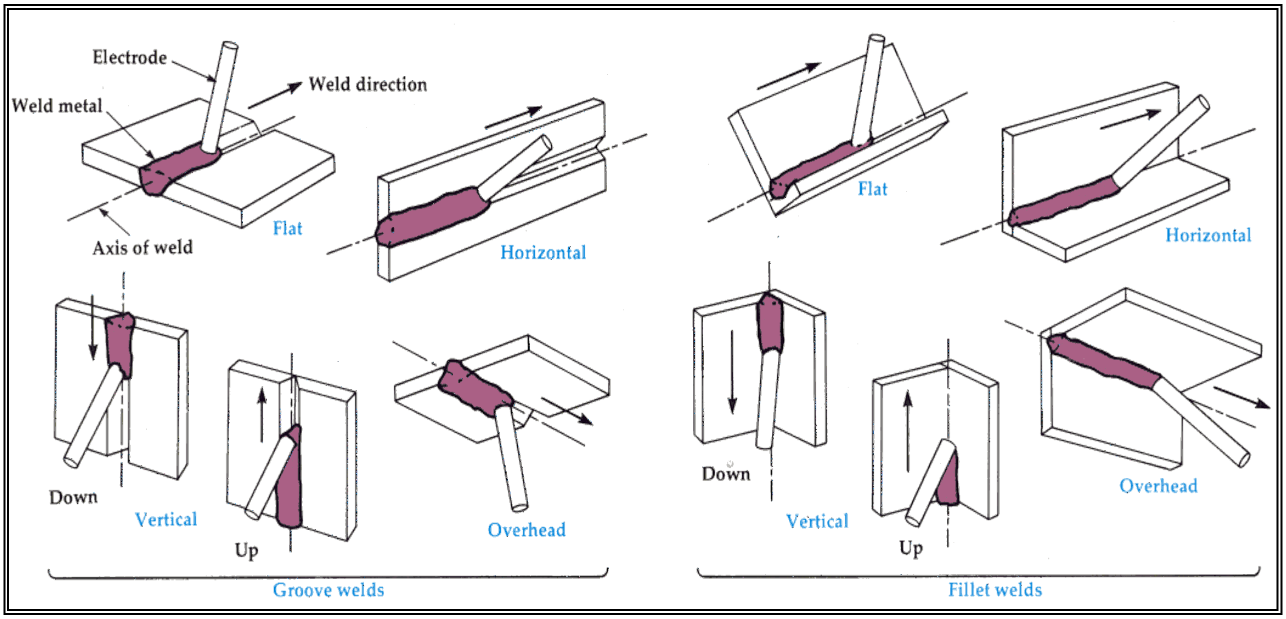
When welds are specified on fabrication drawings a set of symbols are used to describe the type and size of the weld. They can typically be described as a simplified cross section of the actual weld. Some representative symbols are shown below. A complete set of symbols is given in a standard published by the American Welding Society.

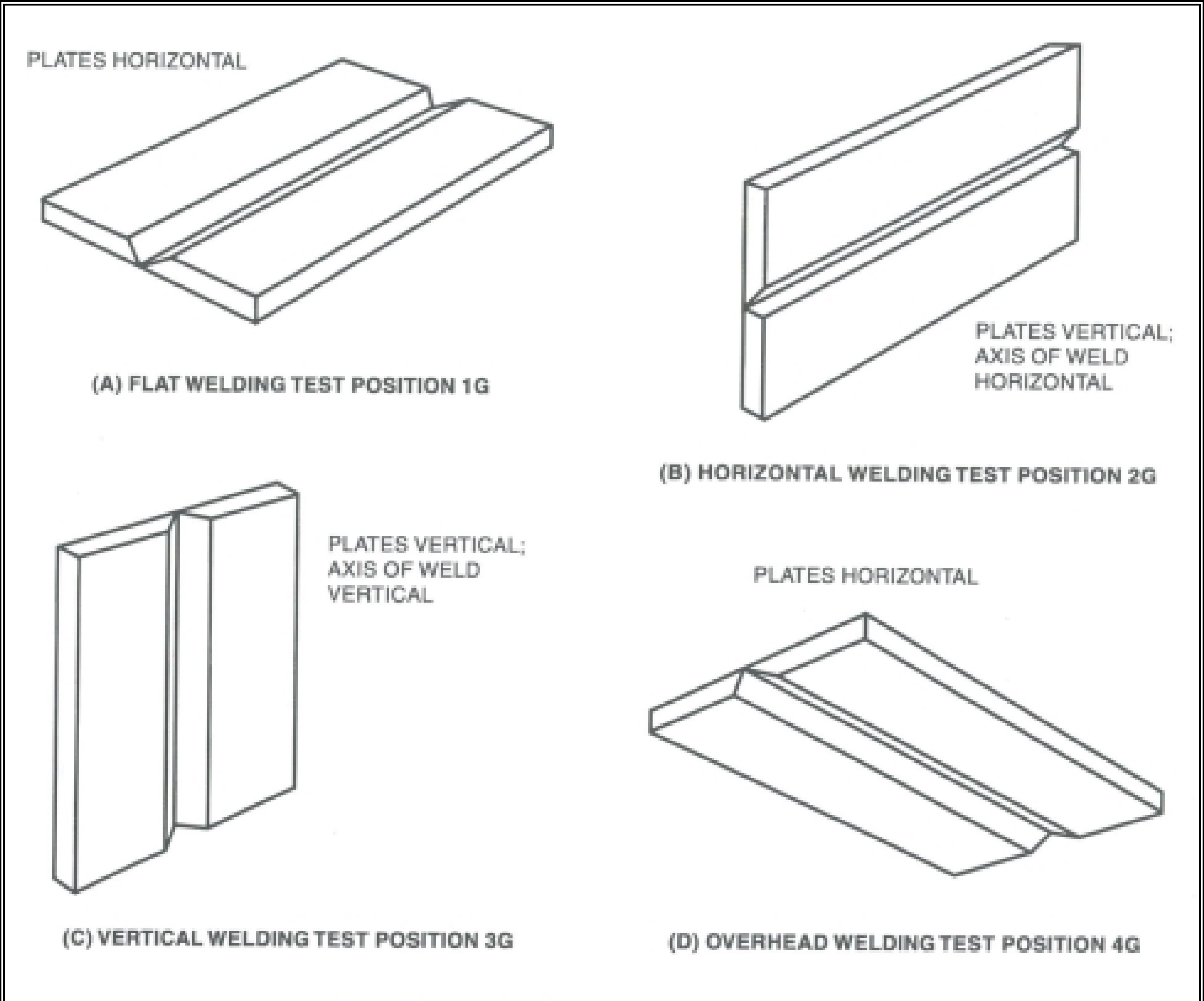


Weld Qualifications:

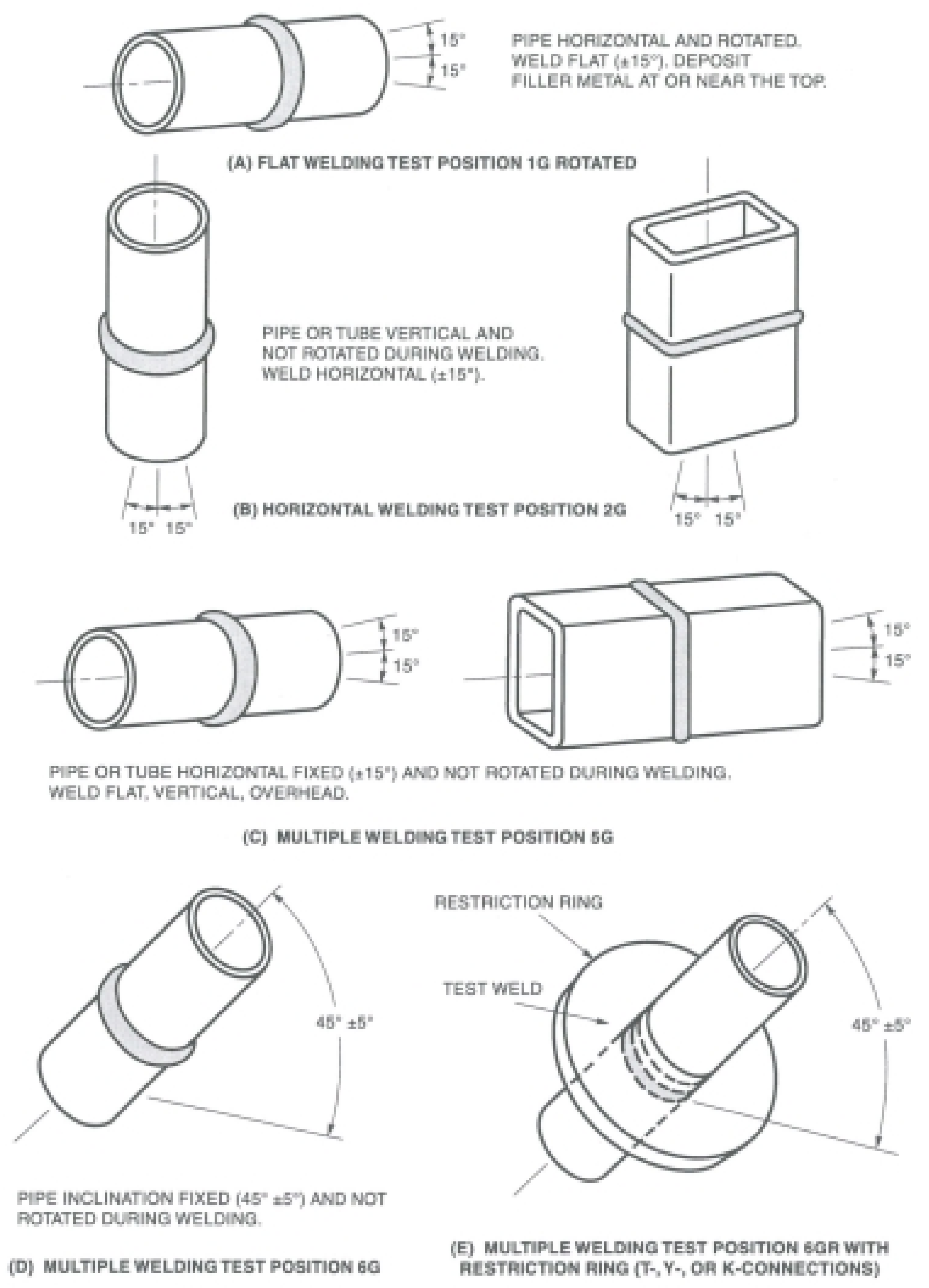
Most fabrication documents require qualification of welding procedures and welders. AWS Code D1.1 is the governing document for structural steel welding. A welding procedure specification (WPS) provides detail welding conditions for a specific application containing the essential variables that require requalification of procedures when the variables are changed beyond specified limits. Typical weld procedures should, at a minimum, contain information about the base materials that are to be welded, the welding process, the filler metal designation, type of current and range, arc voltage and travel speed, joint design and tolerances, surface preparation, positions of welding, preheat and interpass temperatures, interpass cleaning and post weld heat treat as needed.

The welding positions as illustrated below are also important and are taken into account in certifying welders. Flat (1G/1F), Horizontal (2G/2F), Vertical (3G/3F), Overhead (4G/4F) positions are the most common designations along with 6G (pipe-groove welded in a fixed, 45 degree angle position).





Positions of Test Plates for Groove Welds



Positions of Test Pipe or Tubing for Groove Welds

Actual welding parameters used to produce an acceptable test joint and the results of the qualification tests (nondestructive, mechanical, chemical and metallurgical as needed per the applicable codes) are documented in a procedure qualification record (PQR). Welders are required to take a practical exam to demonstrate their ability to produce sound welds by welding up a plate or a pipe coupon. These samples are then submitted to a test lab for either radiography or mechanical testing to obtain welder performance qualifications (WPQ).
A sample Welding Procedure (WPS), which was qualified by testing and hence became a weld procedure (PQR), is included along with the accompanying Welder Qualification record (WPQ).

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☒
PREQUALIFIED____QUALIFIED BY TESTING X
or PROCEDURE QUALIFICATION RECORD (PQR) Yes ☒

Identification # TIG CS
Revision 0 Date 1/1/06 By —
Authorized by Semih Genculu Date 1/106
Type Manual X Semi-Automatic ☐
Machine ☐ Automatic ☐

Company Name ABC Company
Welding Process(es) GTAW
Supporting PQR No.(s) TIG CS-1

JOINT DESIGN USED
Type: Double-V
Single ☐ Double Weld ☒
Backing Yes ☒ No ☐
Backing Material Weld Metal
Root Opening 0 - 1/8" Root Face Dimension —
Groove Angle 60° Radius (J-U)
Back Gouging: Yes X No ☐ Method

BASE METALS
Material Spec. SA570
Type or Grade Grade 50
Thickness Groove 3/16" Fillet —
Diameter (Pipe) —

FILLER METALS
AWS Specification SFA5.18
AWS Classification ER70S-6

SHIELDING
Flux N/A Gas Argon
Composition 100
Electrode-Flux (Class) N/A Flow Rate 30 cfh
Gas Cup Size 3/8"

PREHEAT
Preheat Temp., Min. 60°
Interpass Temp., Min. 60° Max. N/A

POSITION
Position of Groove 1G Fillet
Vertical Progression: Up ☐ Down ☐
N/A

ELECTRICAL CHARACTERISTICS
Transfer Mode (GMAW) Short-Circuiting ☐
Globular ☐ Spray ☐
Current: AC ☐ DCEP ☐ DCEN X Pulsed ☐
Other -
Tungsten Electrode (GTAW)
Size: 3/32"
Type: 2% Thoriated

TECHNIQUE
Stringer or Weave Bead Stringer
Multi-pass or Single Pass (per side) Single
Number of Electrodes Single
Electrode Spacing Longitudinal —
Lateral —
Angle —
Contact Tube to Work Distance —
Peening N/A
Interpass Cleaning N/A

POSTWELD HEAT TREATMENT
Temp. No PWHT
Time —

WELDING PROCEDURE

Pass or Weld Layer(s)	Filler Metals			Current		Volts	Travel Speed	Joint Details
	Process	Class	Diam.	Type & Polarity	Amps or Wire Feed Speed			
Single/Side	GTAW	ER70S-6	3/32"	DCSP	110A	24	Manual	Double-V With 60° Groove

Procedure Qualification Record (PQR) # TIG CS-1
Test Results

TENSILE TEST

Specimen No.	Width (in)	Thickness (in)	Area (in^2)	Ultimate Tensile Load, lbs	Ultimate Unit Stress, psi	Character of Failure and Location
Tensile 1	0.750	0.180	0.1350	10,000	74,100	Ductile, B.Metal
Tensiel 2	0.750	0.180	0.1350	10,100	74,800	Ductile, B.Metal

GUIDED BEND TEST

Specimen No.	Type of Bend	Results	Remarks
1	Face	Acceptable	
2	Face	Acceptable	
3	Root	Acceptable	
4	Root	Acceptable	

VISUAL INSPECTION

Appearance Acceptable
Undercut None
Piping Porosity None
Convexity Acceptable
Test Date 1/10/2006
Witnessed by Weld Supervisor

Other Tests N/A

Radiographic-Ultrasonic Examination

RT Report No: ABC123 Result Acceptable
UT Report No: — Result ______

FILLET WELD TEST RESULTS N/A

Min. size multi. pass ______ Max. size single pass ______
Macroetch Macroetch
1. ______ 3. ______ 1. ______ 3. ______
2. ______ 2. ______

All-Weld-Metal Tension Test N/A

Tensile Strength, psi ______
Yield point/strength, psi ______
Elongation in 2 in., % ______

Welder's Name Mr. TIG Welder Clock No. — Stamp No. 1234
Tests conducted by Testing Lab, Inc. Test No. ABC123

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 ANSI/AWS D1.1/D1.1M, (2004) Structural Welding Code – Steel

Signed ABC Company
Manufacturer or Contractor
By ______
Title ______
Date ______

WELDER OR TACK WELDER QUALIFICATION

Name Mr. TIG welder S.S. No. — Identification No. 1234
Welding Procedure Specification No. TIG CS Rev. 0 Date 1/10/2006

VARIABLES	RECORD ACTUAL VALUES USED IN QUALIFICATION	QUALIFICATION RANGE
Process/Type [Table 4.11, Item (1)]	GTAW	
Electrode (single or multiple) [Table 4.11, Item (8)]	Single	GTAW
Current/Polarity	DC SP	
Position [Table 4.11, Item (4)]	1G (Flat)	Flat
Weld Progression [Table 4.11, Item (6)]	N/A	N/A
Backing (YES OR NO)[Table 4.11, Item (7)]	Yes	With
Material/Spec.	SA570, Gr. 50	
Base Metal		
Thickness: (Plate)		
Groove	3/16"	0.125" – 0.375"
Fillet	—	Unlimited
Thickness (Pipe/Tube)		
Groove	—	0.125" – 0.375"
Fillet	—	Unlimited
Diameter: (Pipe)		
Groove	—	Over 24" Diameter w/Backing
Fillet	—	Unlimited
Filler Metal [Table 4.11, Item (3)]		
Spec. No.	SFA 5.18	
Class	ER70S-6	
F-No. Table 4.11, Item (2)]	6	6
Gas/Flux Type [Table 4.11, Item (3)]	100% Argon	100% Argon
Other	—	—

VISUAL INSPECTION (4.8.1)
Acceptable YES or NO Yes

Guided Bend Test Results (4.30.5)

Type	Result	Type	Result
Face	Pass	Root	Pass
Face	Pass	Root	Pass

Fillet Test Results (4.30.2.3 and 4.30.4.1)

Appearance: — Fillet Size: —
Fracture Test Root Penetration: — Macroetch: —

Inspected by Test Technician Test Number ABC123
Organization Testing Lab, Inc. Date 1/10/2006

RADIOGRAPHIC TEST RESULTS (4.30.3.1) N/A

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 ANSI/AWS D1.1/D1.1M, (2004) Structural Welding Code - Steel.

Manufacturer or Contractor ABC Company Authorized By Welding Supervisor
Date ______