Welding Defects and Remedies in Steel Material

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There are numerous welding processes including arc welding, electron beam welding, friction welding, laser welding, and resistance welding. This article will concentrate on arc welding, which is the most common technique used to join most steels. Factors affecting weld quality will be discussed and how to avoid common weld defects will be presented.

Arc welding requires striking a low-voltage, high-current arc between an electrode and the 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), 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 after welding.

Gas metal arc welding (GMAW) is also referred to as metal inert-gas (MIG) welding. This process uses an uncoated continuous wire and 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.

In 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) is also known as tungsten inert-gas (TIG). This 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 especially advantageous for thin walled parts.

Shielding gases

The primary purpose of the shielding gas is to protect the molten weld metal from contamination and high temperature oxidation by the surrounding atmosphere. Although plain inert gases such as argon and helium 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.

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 base metal 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 and breaks down into carbon monoxide and free oxygen under the heat of the arc. The oxygen superheats the weld metal transferring across the arc.

Weld quality

Factors that can affect the quality of a welded component include the following:

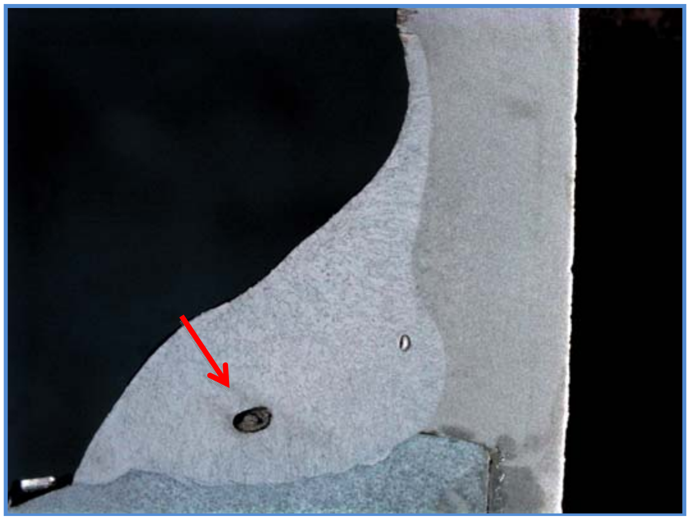
- Design of the weld joint
- Selection of the proper welding process
- Qualification of the welding process (by testing)
- Proper preparation of the joint prior to welding
- Utilization of certified welders
- In-process monitoring of the welding to ensure quality

ARC WELDING DEFECTS

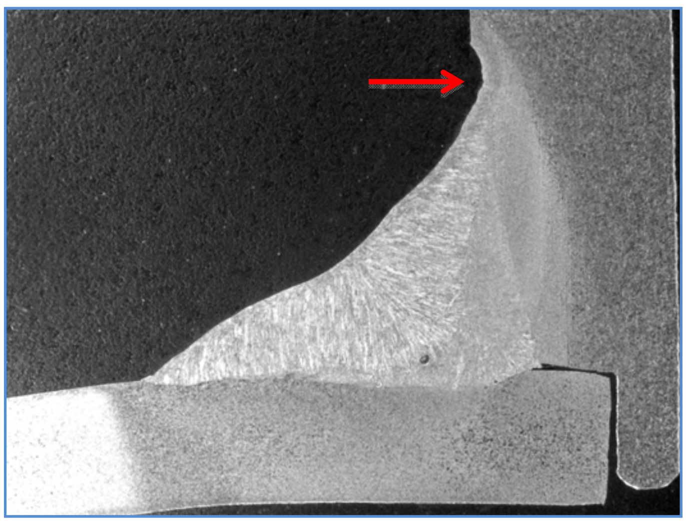
Most welds contain defects (porosity, cracks, slag inclusions, etc.). The question is to determine if they are significant considering the application. Typically, the applicable codes or standards specify the maximum allowable limits of these types of defects in a weld based on the application. Sometimes 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 (such as brittle untempered martensite that 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 have 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 using preheat.

Porosity: Porosity is used to describe cavities or pores caused in the weld during solidification. 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.

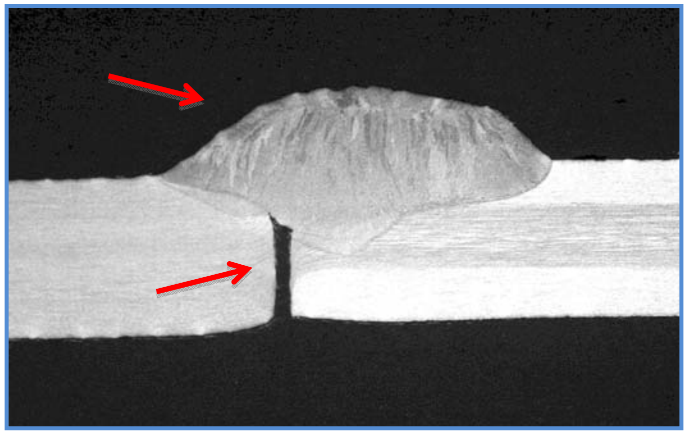
Porosity: gas pockets or voids that are found in welds	
Possible Causes	**Possible Remedies**
Excessive hydrogen, nitrogen or oxygen in welding atmosphere	Use low hydrogen welding process, filler metals high in deoxidizers, increase shielding gas flow
High solidification rate	Use preheat or increase 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
Inadequate gas coverage	Check for proper gas coverage Use a wind screen (when outdoors)
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

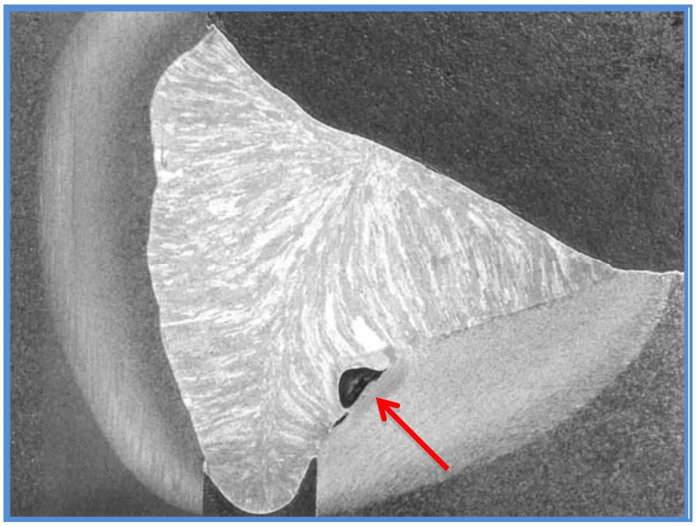


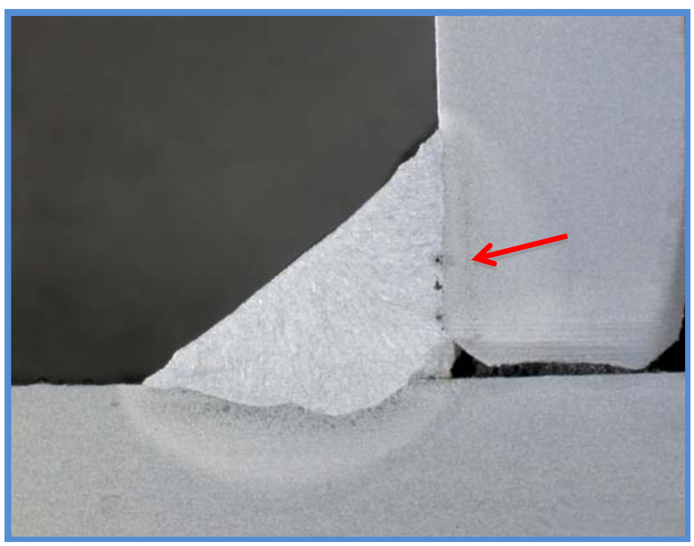
Undercut: Undercut occurs when a groove that is formed adjacent to the weld as a result of the melting of the base metal remains unfilled. The causes are usually associated with incorrect electrode angles, incorrect weaving technique, and excessive current and/or travel speed. Undercut can be avoided by using proper welding technique and parameters. It can be repaired by welding up the resultant groove with a smaller electrode. An example is shown in the macrograph below (at the toe of the fillet weld).



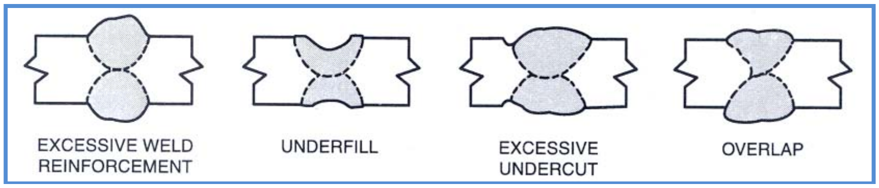
Incomplete fusion/penetration: Although these terms are sometimes used interchangeably, lack of fusion occurs when the weld and base metal fail to adequately fuse together. It can also be encountered between weld passes. It may be caused by not raising the temperature of the base metal or previously 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 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. They are internal discontinuities that are difficult to detect. These defects are usually caused by incorrect welding parameters, such as too low of a welding current, insufficient preheat, too fast of a welding speed, incorrect joint preparation, short arc length or insufficient electrode size. This type of defect can only be repaired by grinding or gouging out the area and re-welding. The first macrograph below shows a butt weld with excessive reinforcement and incomplete penetration. The second macrograph shows lack of penetration to the root of a weld joint, and the third macrograph illustrates lack of fusion to the vertical member of a fillet weld.

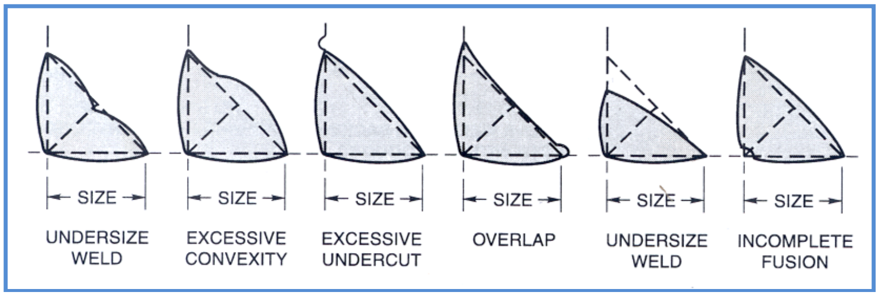




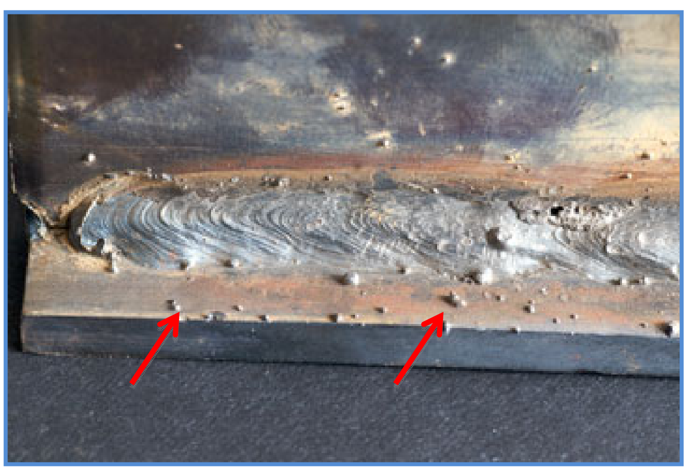


Weld profile: Geometric imperfections such as the profile of a finished weld may have a considerable effect on the performance under dynamic loading conditions. Overlap, excessive reinforcement or misalignment are indications of poor workmanship and can provide stress concentration points where fatigue cracks can initiate. Underfill is a depression on the weld face extending below the surface of the base metal. Misalignment is generally caused by a fit-up problem. Overlap is the protrusion of unfused weld metal beyond the weld toe or weld root. Since overlap forms a mechanical notch it should be repaired by grinding off excess weld metal and smoothly blending the surface to the base metal. Excessively concave or convex welds can be repaired either by filling with further weld metal or grinding back to remove it.
Typical unacceptable butt and fillet weld profiles are shown below.

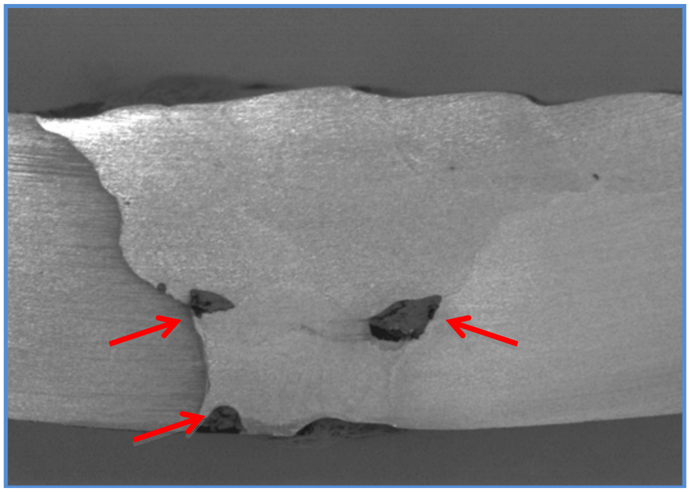




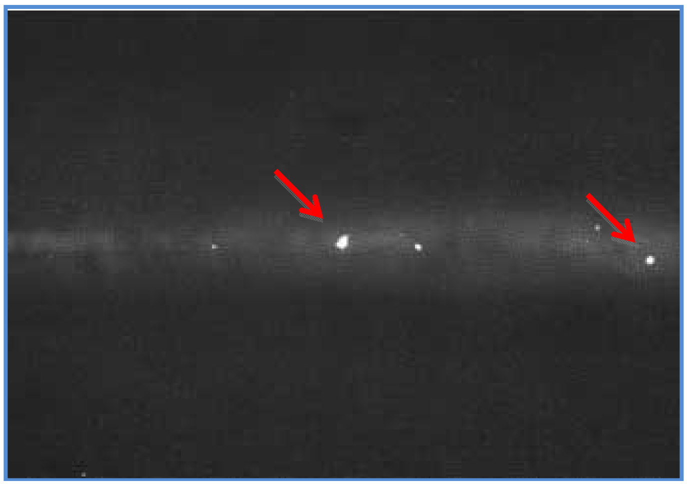
Arc strikes: They are caused by the unintentional melting of the base metal outside the weld deposit area by the welding arc. It can create localized hard or soft spots, cracking or undercut. Another welder-induced defect is weld spatter. Weld spatter is metal drops expelled from the weld that stick to surrounding surfaces. It usually occurs when excessive welding current, long arc or welding voltage is used. Below photographs show arc strikes and weld spatter near fillet welds.



Slag inclusions: One of the main functions of the flux coating in welding is to produce a slag, which flows freely over the surface of the weld pool and protect it from oxidation. Slag is the residue of the flux coating in arc welding and is principally a deoxidation product from the reaction between the flux, air and surface oxides. However, these oxides become entrapped in the weld metal and need to be cleaned between weld passes (in multi-pass operations) using a chipping hammer or a wire brush since they do not get melted out. Slag inclusions not only reduce the cross sectional area of the weld and reduce its strength, but may also serve as imitation points for fatigue cracks. These imperfections can only be repaired by grinding down and re-welding. The macrograph below illustrates slag residue remaining in a groove weld due to inadequate cleaning between weld passes.



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.



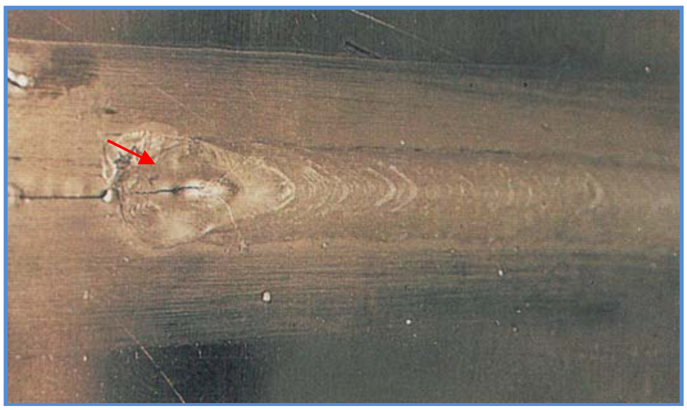
Discontinuity	Possible Causes	Possible Remedies
Undercut	Improper welding technique	Reduce arc length Reduce travel speed Use proper electrode angle
Incomplete Fusion	"Cold" welding Travel speed too slow/fast Improper joint detail	Increase current Use proper travel speed Improve groove angle
Incomplete Joint Penetration	"Cold" welding Travel speed too slow/fast Improper joint detail	Increase current Use proper travel speed Improve groove angle
Excessive Reinforcement	"Cold" welding Travel speed too slow	Increase current Increase travel speed
Underfill	Insufficient weld metal	Reduce travel speed Reduce arc length Use suitable electrode manipulation
Concave Root Surface (Suck-back)	Current too high Arc length too long Root face too small	Reduce current Maintain proper arc length Use proper joint fit-up

Excessive melt through (burn-through)	Excessive root opening Current too high	Reduce root opening Reduce current
Uneven Leg Size	Improper electrode angle	Use appropriate electrode work angle
Overlap	Travel speed too slow Current too low Arc length too short	Use proper travel speed, welding current and arc length
Arc Strikes	Improper welding technique	Initiate arc inside the weld joint
Slag Inclusions	Improper welding technique Excessive welding current Excessive arc length Improper cleaning between passes	Use welding technique to produce smooth weld beads to avoid pockets that can trap slag Use correct current and travel speed to avoid undercutting the sidewall Clean weld between passes
Tungsten Inclusions	Electrode dipping Contact between electrode and filler Current too high Interrupted gas shielding Too high electrode stick-out	Keep gun at a distance to avoid contact with weld puddle Hold rod slightly away from electrode tip Reduce current Maintain adequate shielding Adjust electrode extension from torch collet

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 deposited 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 in the weld or the base metal	
Possible Causes	**Possible Remedies**
Cold cracks (root, toe, underbead and transverse): diffusible hydrogen, brittle structures, restraint stresses	Redry coatings and fluxes, preheat base metals
Cold crack (lamellar tear): inadequate ductility of base metal, high sulfur or inclusion content in the base metal, hydrogen in weld, high tensile stresses in the thickness direction	Use a base metal with higher ductility, lower sulfur and inclusion content, utilize low hydrogen electrodes, modify joint detail and welding process to lower stresses
Hot cracks (crater, longitudinal, center-line): too high welding current, too narrow welding groove	Use proper welding current, fill crater, use appropriate groove angle
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 before cooling to room temperature



Photograph illustrating crater cracking resulting from abrupt weld termination

The effect of carbon equivalent:

The carbon equivalent (C.E.) may be considered as the main factor in estimating the need for preheat. Generally, the higher the carbon content of 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 preheat 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 achieved 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.