Weld Cracking

An Excerpt from
The Fabricators' and Erectors'
Guide to Welded Steel Construction

The James F. Lincoln Arc Welding Foundation

Weld Cracking

Several types of discontinuities may occur in welds or heat affected zones. Welds may contain porosity, slag inclusions or cracks. Of the three, cracks are by far the most detrimental. Whereas there are acceptable limits for slag inclusions and porosity in welds, cracks are never acceptable. Cracks in a weld, or in the vicinity of a weld, indicate that one or more problems exist that must be addressed. A careful analysis of crack characteristics will make it possible to determine the cause and take appropriate corrective measures.

For the purposes of this section, "cracking" will be distinguished from weld failure. Welds may fail due to over-load, underdesign, or fatigue. The cracking discussed here is the result of solidification, cooling, and the stresses that develop due to weld shrinkage. Weld cracking occurs close to the time of fabrication. Hot cracks are those that occur at elevated temperatures and are usually solidification related. Cold cracks are those that occur after the weld metal has cooled to room temperature and may be hydrogen related. Neither is the result of service loads.

Most forms of cracking result from the shrinkage strains that occur as the weld metal cools. If the contraction is restricted, the strains will induce residual stresses that cause cracking. There are two opposing forces: the stresses induced by the shrinkage of the metal, and the surrounding rigidity of the base material. The shrinkage stresses increase as the volume of shrinking metal increases. Large weld sizes and deep penetrating welding procedures increase the shrinkage strains. The stresses induced by these strains will increase when higher strength filler metals and base materials are involved. With a higher yield strength, higher residual stresses will be present.

Under conditions of high restraint, extra precautions must be utilized to overcome the cracking tendencies which are described in the following sections. It is essential to pay careful attention to welding sequence, preheat and interpass temperature, postweld heat treatment, joint design, welding procedures, and filler material. The judicious use of peening as an in-process stress relief treatment may be necessary when fabricating highly restrained members.

Centerline Cracking

Centerline cracking is characterized as a separation in the center of a given weld bead. If the weld bead happens to be in the center of the joint, as is always the case on a single pass weld, centerline cracks will be in the center of the joint. In the case of multiple pass welds, where several beads per layer may be applied, a centerline crack may not be in the geometric center of the joint, although it will always be in the center of the bead (Figure 1).
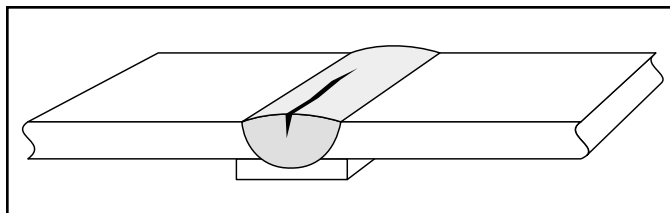

Figure 1 *Centerline cracking*

Centerline cracking is the result of one of the following phenomena: **segregation induced cracking, bead shape induced cracking**, or **surface profile induced cracking**. Unfortunately, all three phenomena reveal themselves in the same type of crack, and it is often difficult to identify the cause. Moreover, experience has shown that often two or even all three of the phenomena will interact and contribute to the cracking problem. Understanding the fundamental mechanism of each of these types of centerline cracks will help in determining the corrective solutions.

Segregation induced cracking occurs when low melting point constituents such as phosphorous, zinc, copper and sulfur compounds in the admixture separate during the weld solidification process. Low melting point components in the molten metal will be forced to the center of the joint during solidification, since they are the last to solidify and the weld tends to separate as the solidified metal contracts away from the center region containing the low melting point constituents.

When centerline cracking induced by segregation is experienced, several solutions may be implemented. Since the contaminant usually comes from the base material, the first consideration is to limit the amount of contaminant pick-up from the base material. This may be done by limiting the penetration of the welding process. In some cases, a joint redesign may be desirable. The extra penetration afforded by some of the processes is not necessary and can be reduced. This can be accomplished by using lower welding currents.
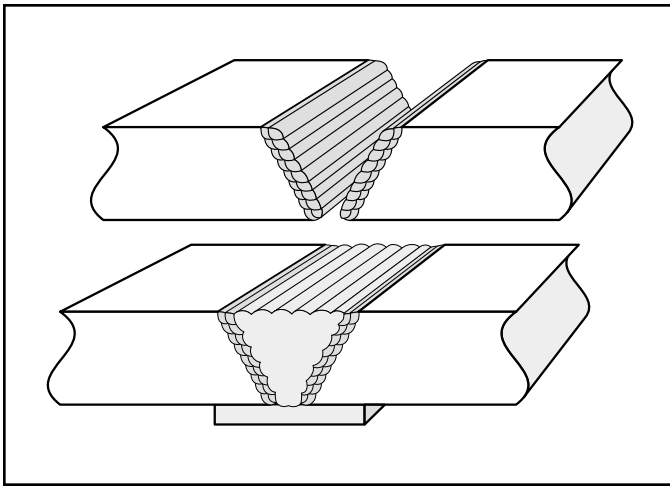
Figure 2 Buttering layers

A buttering layer of weld material (Figure 2), deposited by a low energy process such as shielded metal arc welding, may effectively reduce the amount of pick-up of contaminant into the weld admixture.

In the case of sulfur, it is possible to overcome the harmful effects of iron sulfides by preferentially forming manganese sulfide. Manganese sulfide (MnS) is created when manganese is present in sufficient quantities to counteract the sulfur. Manganese sulfide has a melting point of 2,900°F. In this situation, before the weld metal begins to solidify, manganese sulfides are formed which do not segregate. Steel producers utilize this concept when higher levels of sulfur are encountered in the iron ore. In welding, it is possible to use filler materials with higher levels of manganese to overcome the formation of low melting point iron sulfide. Unfortunately, this concept cannot be applied to contaminants other than sulfur.
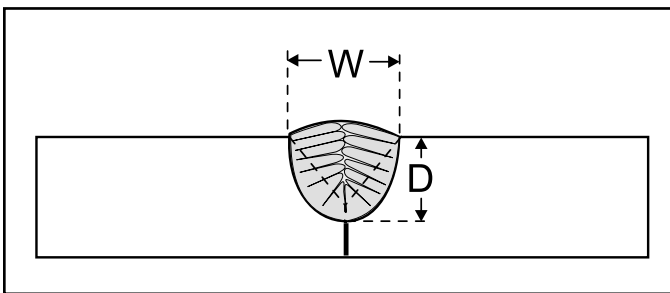

Figure 3 Bead shape induced cracking

The second type of centerline cracking is known as **bead shape induced cracking**. This is illustrated in Figure 3 and is associated with deep penetrating processes such as SAW and CO_2 shielded FCAW. When a weld bead is of a shape where there is more depth than width to the weld cross section, the solidify-

ing grains growing perpendicular to the steel surface intersect in the middle, but do not gain fusion across the joint. To correct for this condition, the individual weld beads must have at least as much width as depth. Recommendations vary from a 1:1 to a 1.4:1 width-to-depth ratio to remedy this condition. The total weld configuration, which may have many individual weld beads, can have an overall profile that constitutes more depth than width. If multiple passes are used in this situation, and each bead is wider than it is deep, a crack-free weld can be made.

When centerline cracking due to bead shape is experienced, the obvious solution is to change the width-to-depth relationship. This may involve a change in joint design. Since the depth is a function of penetration, it is advisable to reduce the amount of penetration. This can be accomplished by utilizing lower welding amperages and larger diameter electrodes. All of these approaches will reduce the current density and limit the amount of penetration.
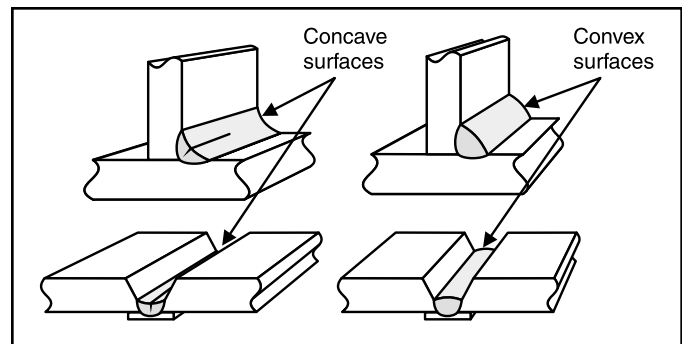

Figure 4 Surface profile induced cracking

The final mechanism that generates centerline cracks is **surface profile conditions**. When concave weld surfaces are created, internal shrinkage stresses will place the weld metal on the surface into tension. Conversely, when convex weld surfaces are created, the internal shrinkage forces will pull the surface into compression. These situations are illustrated in Figure 4. Concave weld surfaces frequently are the result of high arc voltages. A slight decrease in arc voltage will cause the weld bead to return to a slightly convex profile and eliminate the cracking tendency. High travel speeds may also result in this configuration. A reduction in travel speed will increase the amount of fill and return the surface to a convex profile. Vertical-down welding also has a tendency to generate these crack-sensitive, concave surfaces. Vertical-up welding can remedy this situation by providing a more convex bead.

Heat Affected Zone Cracking

Heat affected zone (HAZ) cracking (Figure 5) is characterized by separation that occurs immediately adjacent to the weld bead. Although it is related to the welding process, the crack occurs in the base material, not in the weld material. This type of cracking is also known as "underbead cracking," "toe cracking," or "delayed cracking." Because this cracking occurs after the steel has cooled below approximately 400°F, it can be called "cold cracking", and because it is associated with hydrogen, it is also called "hydrogen assisted cracking."
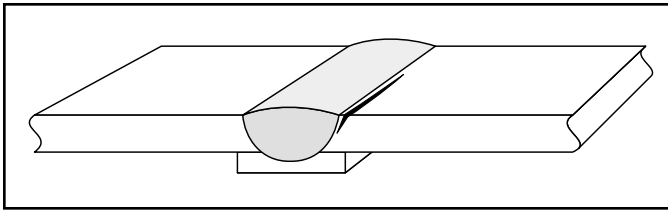
Figure 5 *Heat affected zone cracking*

In order for heat affected zone cracking to occur, three conditions must be present simultaneously: there must be a sufficient level of hydrogen; there must be a sufficiently sensitive material involved; and, there must be a sufficiently high level of residual or applied stress. Adequate reduction or elimination of one of the three variables will generally eliminate heat affected zone cracking. In welding applications, the typical approach is to limit two of the three variables, namely the level of hydrogen and the sensitivity of the material.

Hydrogen can enter into a weld pool from a variety of sources. Moisture and organic compounds are the primary sources of hydrogen. It may be present on the steel, the electrode, in the shielding materials, and is present in the atmosphere. Flux ingredients, whether on the outside of electrodes, inside the core of electrodes, or in the form of submerged arc or electroslag fluxes, can absorb moisture, depending on storage conditions and handling practices. To limit hydrogen content in deposited welds, welding consumables must be properly maintained, and welding must be performed on surfaces that are clean and dry.

The second necessary condition for heat affected zone cracking is a sensitive microstructure. The area of interest is the heat affected zone that results from the thermal cycle experienced by the region immediately surrounding the weld nugget. As this area is heated by the welding arc during the creation of the weld pool, it is transformed from its room temperature structure of ferrite to the elevated temperature structure of austenite. The subsequent cooling rate will determine the resultant HAZ properties. Conditions that encourage the development of crack sensitive microstructures include high cooling rates and higher hardenability levels in the steel. High cooling rates are encouraged by lower heat input welding procedures, greater base metal thicknesses, and colder base metal temperatures. Higher hardenability levels result from greater carbon contents and/or alloy levels. For a given steel, the most effective way to reduce the cooling rate is by raising the temperature of the surrounding steel through preheat. This reduces the temperature gradient, slowing cooling rates, and limiting the formation of sensitive microstructures. Effective preheat is the primary means by which acceptable heat affected zone properties are created, although heat input also has a significant effect on cooling rates in this zone.

The residual stresses of welding can be reduced through thermal stress relief, although for most structural applications, this is economically impractical. For complex structural applications, temporary shoring and other conditions must be considered, as the steel will have a greatly reduced strength capacity at stress relieving temperatures. For practical applications, heat affected zone cracking will be controlled by effective low hydrogen practices, and appropriate preheats.

For HAZ hydrogen cracking to occur, it is necessary for the hydrogen to migrate into the heat affected zone, which takes time. For this reason, the D1.1 Code (D1.1-96, paragraph 6.11) requires a delay of 48 hours after completion of welds for the inspection of welds made on A514, A517 and A709 Gr. 100 and 100W steels, known to be sensitive to hydrogen assisted heat affected zone cracking.

With time, hydrogen diffuses from weld deposits. Sufficient diffusion to avoid cracking normally takes place in a few weeks, although it may take many months depending on the specific application. The concentrations of hydrogen near the time of welding are always the greatest, and if hydrogen induced cracking is to occur, it will generally occur within a few days of fabrication. However, it may take longer for the cracks to grow to sufficient size to be detected.

Although a function of many variables, general diffusion rates can be approximated. At 450°F, hydrogen diffuses at the rate of approximately 1 in. per hour. At 220°F, hydrogen diffuses the same 1 in. in approximately 48

hours. At room temperature, typical diffusible hydrogen rates are 1 in. per 2 weeks. If there is a question regarding the level of hydrogen in a weldment, it is possible to apply a postweld heat treatment commonly called "post heat." This generally involves the heating of the weld to a temperature of 400 - 450°F, holding the steel at that temperature for approximately one hour for each inch of thickness of material involved. At that temperature, the hydrogen is likely to be redistributed through diffusion to preclude further risk of cracking. Some materials, however, will require significantly longer than 1 hour per inch. This operation may not be necessary where hydrogen has been properly controlled, and it is not as powerful as preheat in terms of its ability to prevent underbead cracking. In order for post heat operations to be effective, they must be applied before the weldment is allowed to cool to room temperature. Failure to do so could result in heat affected zone cracking prior to the application of the post heat treatment.

Transverse Cracking

Transverse cracking, also called cross cracking, is characterized as a crack within the weld metal perpendicular to the direction of travel (Figure 6). This is the least frequently encountered type of cracking, and is generally associated with weld metal that is higher in strength, significantly overmatching the base material. This type of cracking can also be hydrogen assisted, and like the heat affected zone cracking described earlier, transverse cracking is also a factor of excessive, hydrogen, residual stresses, and a sensitive microstructure. The primary difference is that transverse cracking occurs in the weld metal as a result of the longitudinal residual stress.
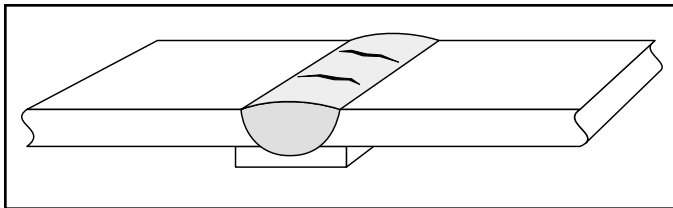
Figure 6 *Transverse cracking*

As the weld bead shrinks longitudinally, the surrounding base material resists this force by going into compression. The high strength of the surrounding steel in compression restricts the required shrinkage of the weld material. Due to the restraint of the surrounding base material, the weld metal develops longitudinal stresses which may facilitate cracking in the transverse direction.

When transverse cracking is encountered, a review of the low hydrogen practice is warranted. Electrode storage conditions should be carefully reviewed. If this is a problem, a reduction in the strength of the weld metal will usually solve transverse cracking problems. Of course, design requirements must still be met, although most transverse cracking results from weld metal over matching conditions.

Emphasis is placed upon the weld metal because the filler metal may deposit lower strength, highly ductile metal under normal conditions. However, with the influence of alloy pick-up, it is possible for the weld metal to exhibit extremely high strengths with reduced ductility. Using lower strength weld metal is an effective solution, but caution should be taken to ensure that the required joint strength is attained.

Preheat may have to be applied to alleviate transverse cracking. The preheat will assist in diffusing hydrogen. As preheat is applied, it will additionally expand the length of the weld joint, allowing the weld metal and the joint to contract simultaneously, and reducing the applied stress to the shrinking weld. This is particularly important when making circumferential welds. When the circumference of the materials being welded is expanded, the weld metal is free to contract along with the surrounding base material, reducing the longitudinal shrinkage stress. Finally, post weld hydrogen release treatments that involve holding the steel at 250-450°F for extended periods of time (generally 1 hour per in. of thickness) will assist in diffusing any residual hydrogen.