Girish P. Kelkar, Ph.D.
(562) 743-7576
girish@welding-consultant.com
www.welding-consultant.com

Weld Cracks – An Engineer's Worst Nightmare

There are a variety of physical defects such as undercut, insufficient fusion, excessive deformation, porosity, and cracks that can affect weld quality. Of those defects, cracks are considered to be the worst since even a small crack can grow and lead to failure. All welding standards show zero tolerance for cracks where as the other defects are tolerated within certain limits. There are three requirements for cracks to form and grow: a stress-raising defect, tensile stress, and material with low fracture toughness. Microscopic defect locations are available in practically all welds including geometric features and weld chemistry that can raise the local stress enough to induce a crack. That leaves the engineer to work with the stress environment and toughness: if either of the two can be effectively controlled then cracks can be prevented from initiating and growing. Toughness is a measure of resistance to crack growth; resistance can be provided by blunting of the crack tip in ductile materials. However, if applied strain rate is very high (as would be the case when a spot weld cools at the end of the pulse) and the stress field is multi-axial, even ductile materials exhibit poor toughness and produce rapid crack growth. Hard materials, such as martensite formed during cooling of steels, are brittle and have poor toughness. Toughness can be improved by controlling alloy chemistry and post-weld heat treatment. Stresses can be reduced by changing the joint design to ensure that the weld is under very low tensile load, and preferably, have a compressive load at possible crack locations. Joint deigns and fillet shapes can be controlled to minimize stress concentrators that assist in initiation of cracks.

Cracks that form in and around the weld can be distinguished into two main categories, hot cracks and cold cracks. Cracks can also form in and near the weld during use and can be caused due to fatigue or corrosion. Cracks that form during the cooling process are referred to as hot cracks and cracks whose formation is delayed are called cold cracks. To identify how and why a particular crack formed, we need to dig deeper into weld design, identify crack locations, and evaluate related metallurgy. Once the root cause or causes are identified, appropriated action can be taken to avoid crack formation.

Hot Cracks

As the name implies, these cracks form while the weld temperature is high and are usually related to solidification; crack growth is typically assisted by cooling stresses induced in the weld. Solidification cracking occurs when there is low solubility for alloying elements in the primary phases that solidify during cooling. As the solidifying grains grow, they exclude the impurities and/or minor alloying elements and push them towards the center of the weld. The impurities/alloying elements often do react with the dominant element to form low melting phases that generally have poor strength. Typical examples would be Iron-Sulfur compounds in steels and Aluminum-Copper compounds in Aluminum alloys. Hot cracks typically occur in the throat of the weld (see Figure 1) and can extend along the length of the weld, producing longitudinal cracks. In some fusion weld applications, such cracks can also form at the end of the weld line and produce a star-shaped pattern of cracks radiating outwards; such cracks are referred to as crater cracks. In some Aluminum alloys, hot cracks form in the HAZ (heat affected zone) adjacent to the fusion zone. Since the segregation of phases occurs along grain boundaries, hot cracks grow intergranularly. Common alloy systems that suffer from hot cracking are steels and aluminum alloys. Carbon steels with excessive sulfur are prone to hot cracking and such tendencies can be reduced by using either steel with low sulfur or with high enough Manganese that can combine with sulfur and render it inactive. Hot cracks are also found in laser welded 316 austenitic stainless steels that solidify as primary austenite. Weld cracking can be avoided by using a filler such 304 or 308 that provides enough ferrite stabilizers; solidifying ferrite has a greater solubility for impurity sulfur and keeps it out of trouble. Aluminum 6061 suffers similar problems that can be remedied in the fusion zone by mixing with 4047/4043 Al alloys.

Hot cracks can also form when the weld is too weak to support the two components and have been observed as root cracks. Analysis of the cracked region under and SEM to identify elemental segregation is the first step in evaluating hot cracks.

Cold Cracks

Cold cracks form in the weld at some point in time after the weld has cooled. Cold cracks usually form either due to excessive stress in the weld or due to hydrogen-diffusion in steels. Elemental hydrogen can diffuse and migrate to dislocations and form pockets to create enough pressure to expand the defect and form a crack. But just the presence of hydrogen is not enough; a microstructure conducive to crack growth is also required. Such microstructure can form in steels that undergo transformation from ferrite to austenite as they are heated during welding and subsequently can form martensite during cooling. Matensite formation is encouraged by a combination of carbon content, alloying elements, and cooling rate. Under some circumstances, cold cracks can form up to 48 hours after welding. Hydrogen-assisted cracking can be reduced by preheating to reduce cooling rate after the weld and post-weld heating to encourage diffusion of hydrogen out of the weld. Such cracks can form in the weld zone but are typically found in HAZ

Some cold cracks can form due to excessive strain in the weld after cooling and are typically observed in welds of very thick cross-section or if the fusion zone alloy is much stronger than the surrounding base metal. Transverse cracks are typical of such situations. Toe cracks that appear to originate at weld/HAZ boundary near the free surface are likely to be caused by a combination of excessive stress and a brittle HAZ. Cold cracks are more likely to be transgranular, i.e., going through the grains rather than along grain boundaries.

Fatigue Cracks

Fatigue cracks can form in regions near the weld due to the residual stress distribution that assists in the formation and growth of such cracks in the presence of external fatigue stress. Fatigue cracks have been observed to grow at locations beyond the HAZ but in a region where the residual surface tensile stresses are produced during weld cooling.

Corrosion Cracks

Stainless steels are considered "stainless" since they have a protective layer of chromium oxide on the surface that prevents any rusting when exposed to moisture. However, at high temperatures of the order of 400-800C, typically those encountered by the HAZ during fusion welding, some of the chromium atoms react with carbon and precipitate out as chromium carbides. These chromium atoms are no longer available to form a protective oxide layer on the surface. In presence of suitable ionic liquid, a galvanic cell corrosion attack can propagate into the matrix along grain boundaries and is evident in cross-sections as a river branching pattern. Such cracks are more likely to form when assisted by tensile stress on the exposed surface. Options to avoid such cracks include use of low-carbon grade steels or if possible, send the entire welded component through a post-weld solution heat treatment to break up the chromium carbides and restore original steel chemistry. Similar cracks are also known to occur in practically all metal systems, for example, corrosion cracks in Al in presence of chlorides, and in brass alloys in the presence of ammonia.

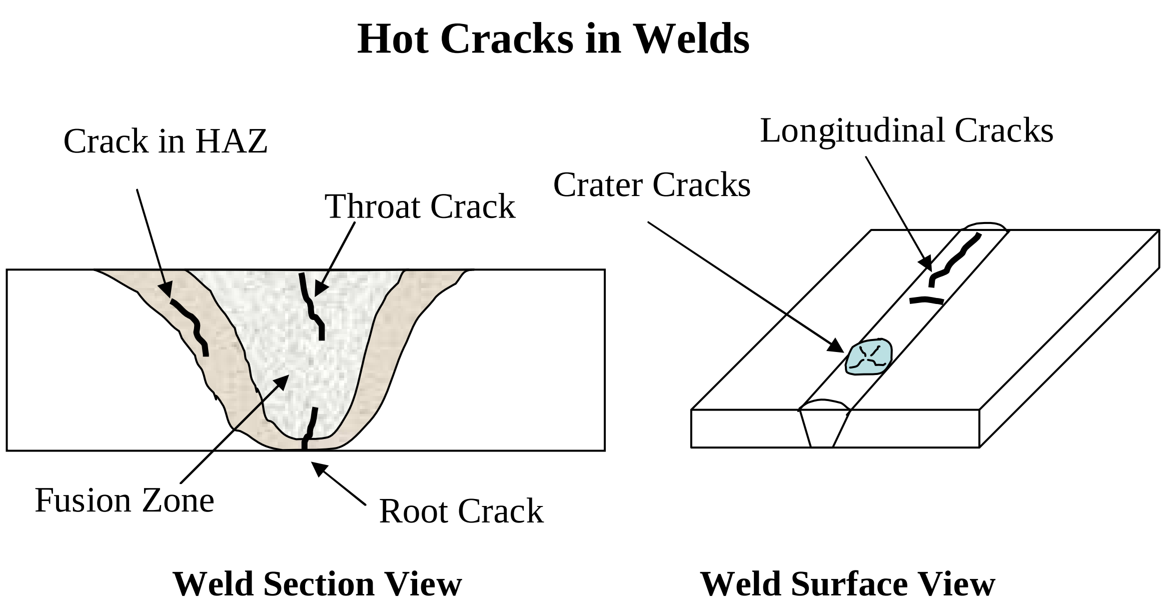

Figure 1. Schematic showing locations of typical hot cracks in welds.

Cold Cracks in Welds

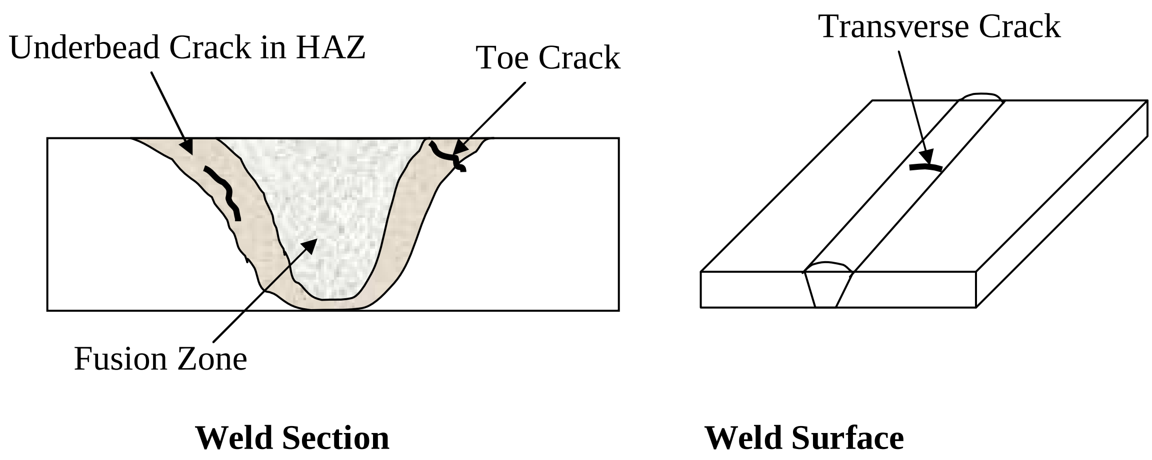

Figure 2. Schematic showing locations of typical cold cracks in welds.

Fatigue and Corrosion Cracks

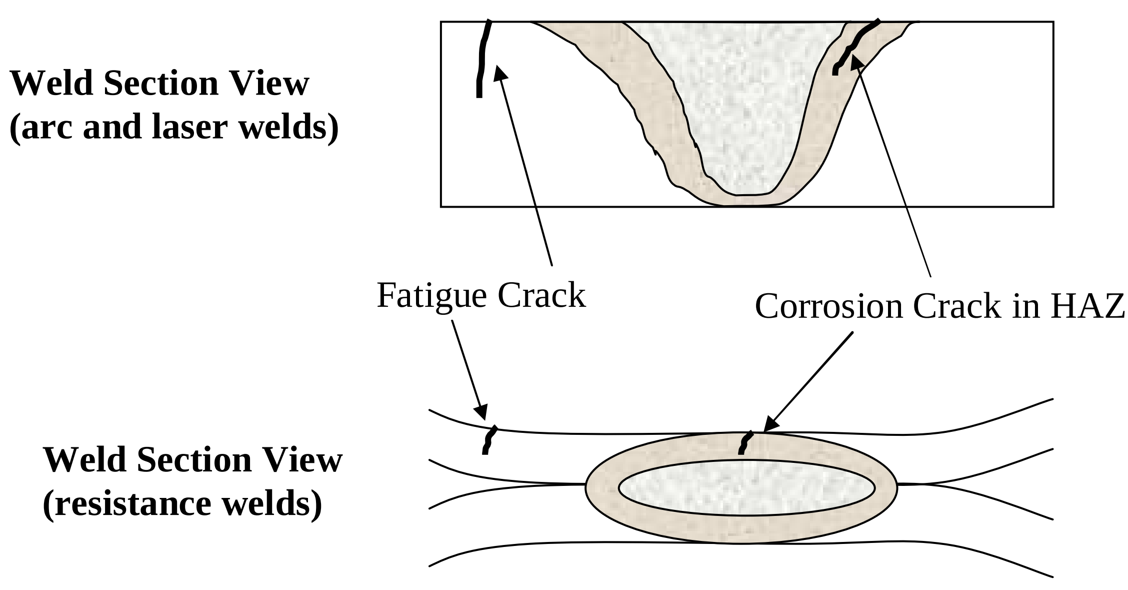

Figure 3. Schematic showing locations of fatigue and corrosion crack in and near the welds.