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Importance of Failure Mode in Welding

Any metallurgical connection, whether it be a solder, braze, solid-state, or fusion weld, is invariably tested after processing to check for quality. Parts can be 100% inspected by a slew of techniques including visual, optical, surface profile checks, leak check, and x-ray inspection. In addition, a fraction of parts is tested to failure by some form of mechanical loading such as pull test, peel test, or burst pressure test. Extended life tests are often simulated by testing parts in vibration or similar form of fatigue loading. When tested to the limit, the parts will fail at the weakest location, based on applied load, stress concentration factors, and material condition. In addition to numeric quality metrics associated with the failure, the mode of failure plays a critical role in understanding of weld quality.

A metallurgical connection can be defined as having three different regions in the vicinity of the joint and can be seen in polished and etched weld sections. The main bonding region, where the two parts to be joined come together, is where all the action happens and is evident as the fusion zone in typical welded connections. In solder/braze joints, the filler metal can be clearly seen as third constituent at the interface. Solid-state bonds are a bit different as there is only a line that separates the two faying surfaces. Adjacent to the joint area is the heat affected zone (HAZ) which is the base materials whose properties have been affected by the welding heat. The HAZ can have distinctly different properties compared to the joint area or the original base material. Beyond the HAZ is the original base material that is unaffected by all the shenanigans at the weld joint.

When a joint is tested to failure, the mechanical loading will usually result in complete separation of the weld into two parts. In some cases, failure may be defined as appearance of a leak path, at which point the test may be aborted. While a corresponding numeric value of strength provides useful information for statistical analysis, the location and mode of separation across the failure location proves to be invaluable to the welding engineer. A weld may fail in the parent metal, in the HAZ, or the in the weld zone itself. Failure in the parent metal is usually considered the preferred mode and implies that the weld joint is stronger than the parent metal. When the test method applies tensile stress on the joint, failure in the parent metal is of the typical cup/cone type failure where the parent metal necks down during the test and ultimately has a catastrophic failure. If the parent metal is brittle, the failure may initiate from the surface flaw and will appear more as fractured surface. However, in the welding world, failure in parent metal is not so common.

Most typical welds will fail at or near the weld joint for multiple reasons. The first is the presence of a stress-concentrating geometry feature such as a sharp angle between parts in an edge weld or overlapping parts in lap welds. In case of fusion welds, a joint with specified partial penetration provides sharp notch that can focus the applied stress as shown in Figure 1. The second reason for failure at the joint is weld defects welds which do not meet design requirements. Such a situation can arise from poor operator training in manual welding, part misalignment in automation, or use of an unqualified welding procedure. Such issues can lead to failures even before part is tested or can be glaringly obvious in metallurgical evaluation of the welds. An example of lack of fusion, possibly due to improper weld setup, can be seen in Figure 2 which shows reasonable fusion along the horizontal leg of the fillet weld while the vertical leg exhibits a complete lack of fusion between the weld filler and the parent metal. On testing, such a weld will make a clean separation along the vertical edge of the fillet. Other fusion welding defects can include undercut, overlap, and underfill. In resistance and ultrasonic welding, excessive force can cause significant and unacceptable surface indentation.

The third reason for failure to occur at or near the weld is the presence of weaker and/or brittle material formed due to the welding heat. The intense rate of heating and subsequent cooling can produce substantial changes to the microstructure that are typically seen in heat-treatment and casting operations. Most materials have controlled levels of minority or impurity elements that are uniformly distributed in the microstructure. However, melting and cooling of metal in the weld area can segregate the minority elements which get pushed to grain boundaries producing locations of weakness. On the other hand, steels with high levels of carbon can become brittle after welding thus producing a microstructure that is brittle and susceptible to rapid crack growth.

Once sufficient stress is reached at the joint, a crack will be initiated at the point of highest stress concentration, and the crack path will be determined by the material and bonding properties. On a weld with lack of fusion across the interface, such as the one shown in Figure 2, the weld will have a clean separation at the interface or between the filler metal and the part. Such a separation is not desirable as it indicates a lack of bonding at the interface. If the weld is designed to be weaker compared to the parent metals, even a good weld may fail in what appears to be the weld interface but will result in a matt finish indicating some transfer of material across the bond line. In some situations, the crack may start near the weld interface but then meander away where it may find an easier path to failure. Close inspection of separated faces will show transfer of material from one part to the other. A resistance lap weld that is showing substantial transfer of material from one part to the other during testing to failure is shown in Figure 3.

Combination of location of failure and type of material transfer is defined as the failure mode. In a stable process, the weld strength should have a narrow distribution and a consistent failure mode. Even at the low values of weld strengths, the failure mode should be the same as that at higher values. Any changes in failure mode, even with weld strength within acceptable limits, is an indication of a process that is moving in the wrong direction or is not robust. While it is typically not a requirement to report failure mode on quality charts, a welding engineer do well to keep track of the failure mode; just might prove to be a canary in the coal mine.

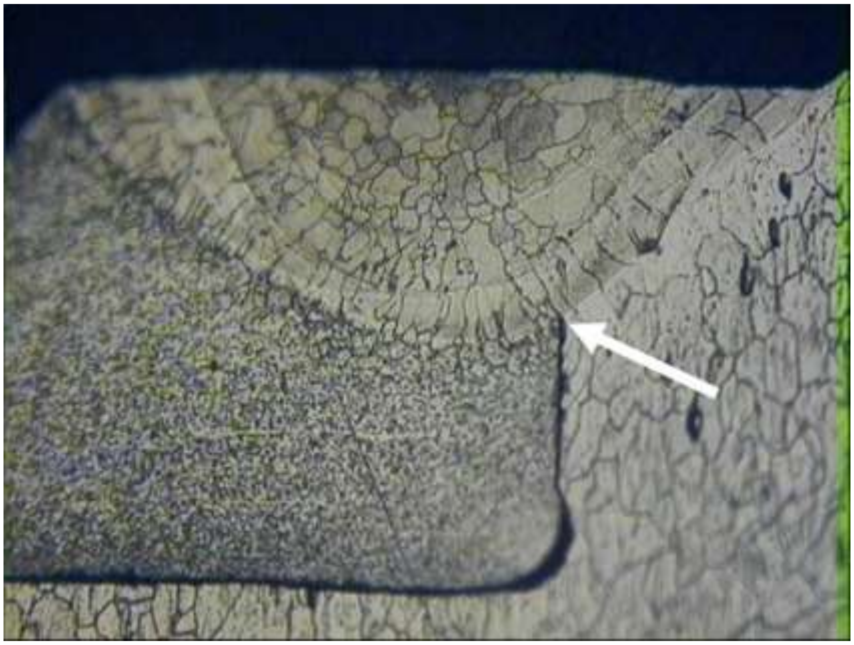

Figure 1. Photo above shows a laser weld with partial penetration that will produce a high stress point (marked with a white arrow) which can lead to crack growth and failure during testing.

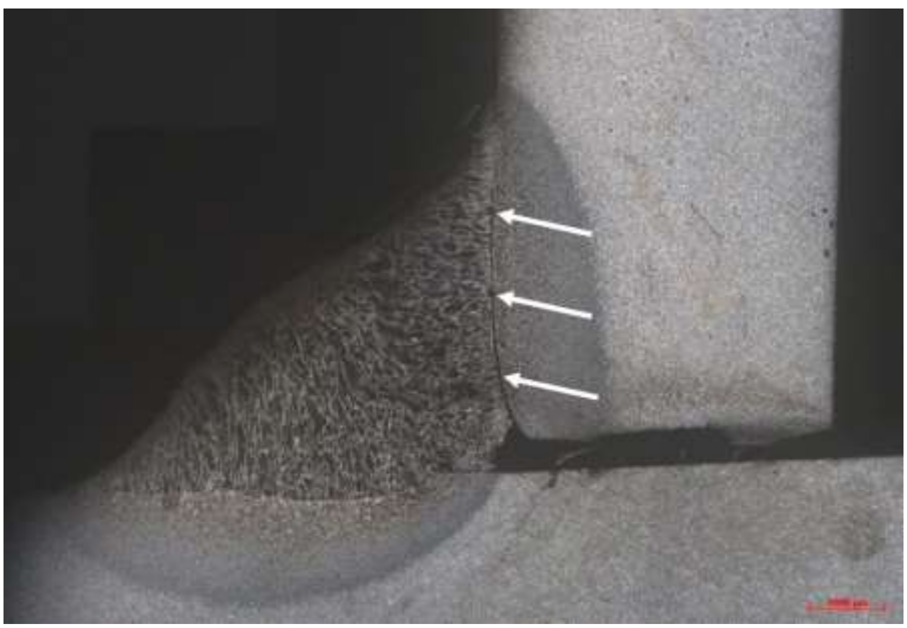

Figure 2. Photo above shows lack of fusion along the vertical edge of a MIG weld which will lead to a clean separation between the part and the fillet when tested to failure.

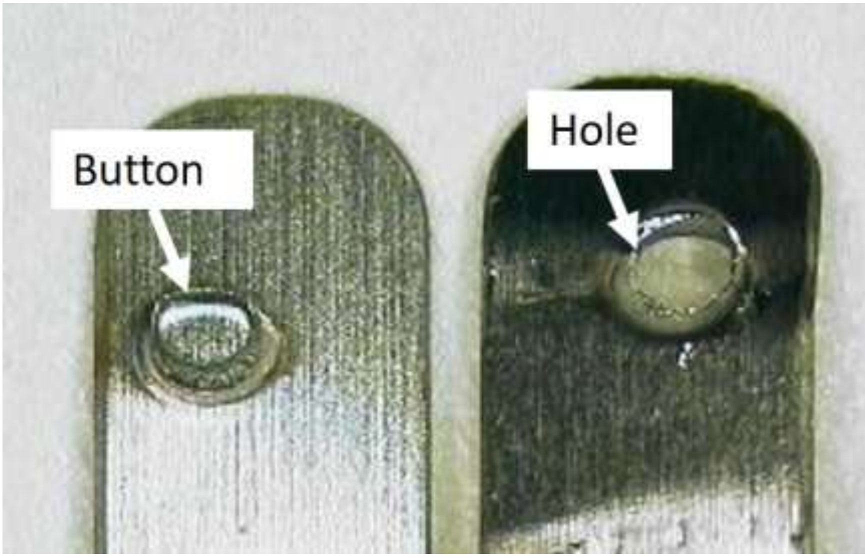

Figure 3. Photo above shows two resistance welded parts after testing to failure. A button is visible on the left and a corresponding hole is visible on right.