

## Welding Metallography - Ferrous Metals

### Introduction

Welding is a crucial joining process with controlled methods to ensure high-quality end results in various applications. Like all processes, welding requires careful control to ensure the integrity of the final product. Throughout history, there have been notable failures of welded structures that highlight the importance of quality assurance. Both non-destructive and destructive tests are employed to study weldments. Metallographic examination can be conducted on-site by grinding and polishing a spot on the surface of a weld, its heat-affected zones, or nearby base metal. This approach is relatively non-destructive. Destructive examination, where a sample is taken from the welded assembly or test coupons, is also commonly performed. Test coupons are used to qualify welders and verify that the chosen techniques and materials will produce a weld with acceptable soundness and mechanical properties. Additionally, postmortems of failed weldments are often examined metallographically after non-destructive tests are completed.

### Welding Process

There are many processes that have been developed to produce welded joints. Most people have seen the stick-electrode process that can be done in the field. But, this is just one of many welding processes. Although welding is a comparatively new technology, forge welding vastly predates all other methods as it dates from the earliest days of metalworking. Aside from forge welding, the other processes date from the 20th century, particularly since 1940. There are both gas welding and cutting processes using an oxyacetylene flame; resistance welding processes, such as spot welding, induction welding, flash welding; arc welding processes such as gas-tungsten-arc (GTA) and metal-inert gas (MIG), covered electrode processes (stick electrode), submerged-arc welding, electroslag welding, electron beam and laser welding, as well as friction welding. Many of these processes have been further modified in a variety of ways. Some of these processes use filler metals, generally of somewhat different composition than the base metal to produce higher strength in the weld. Others use no filler metal, relying only upon the melting of the base metal to produce the joint.

### Weld Terminology

Figure 1 shows a schematic illustrating the basic features of a fusion weld. There are three main regions: the base metal, the heat-affected zone (HAZ) and the weld metal. Regardless of the welding process, substantial heat is generated in welding and melting occurs. The heat input can vary greatly with the welding process used and is influenced by other factors, such as the thickness of the pieces being joined. The welded joint, or weld "nugget" is a casting. When wrought metal is welded, there is a temperature gradient, going from the nugget into

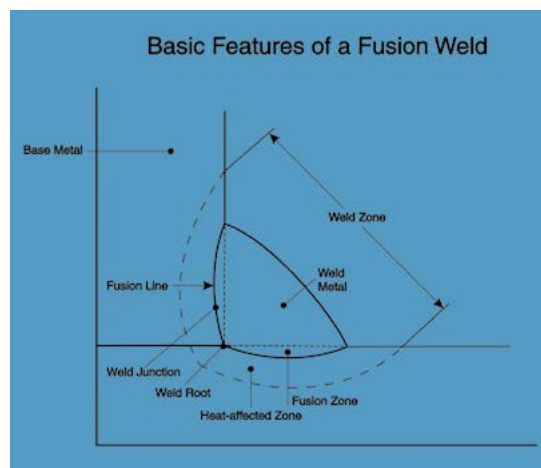


Figure 1. Basic terms related to a fillet weld.

the unaffected base metal, from above the melting point of the metal or alloy to ambient temperature. This temperature gradient can produce many effects depending upon the metals or alloys being joined. Using steels as an example, the weld nugget was created by molten metal, in many cases filler metal, that was heated in the arc until it melted. Solidification can occur under different cooling conditions, depending upon the heat input, whether or not pre-heating or post-heating practices are used, depending upon the mass of the pieces, ambient temperature, and so forth. Naturally, there is a fusion line, the boundary between the cast nugget and the nonmelted base metal. Below the fusion line, the temperature gradually drops to ambient. If the part is made from steel, the heat-affected zone (between the fusion line and the unaffected base metal), or at least part of the heat-affected zone, will be fully austenitic due to temperatures above the upper critical,  $AC_3$ , of the steel. The grains closest to the fusion line will be the largest in size. At lower temperatures, the grain size can be quite small due to recrystallization and nucleation of new fine grains that may, or may not, grow substantially depending upon the temperature that they experience after nucleation. Depending upon the way the steel was deoxidized, columnar grains may be seen. In the region of the HAZ that was heated into the two phase  $\alpha+\gamma$  field, the transformation on cooling may be quite different. For areas heated below the lower critical temperature,  $AC_1$ , the original structure may be tempered or may start to spheroidize. Because the filler metal is a different composition than the base metal, and some melting of the base metal occurs, the composition will vary through the weld to the fusion line. With variations in the phases or constituents and their grain size in the weld nugget and heat affected zone, we can expect to see hardness variations across these gradients.

Cracks may be detected in the weld nugget or in the heat-affected zone. Figure 2 shows a schematic illustrating common terminology for cracks and voids. Use of correct terminology to describe cracks is very important. Many of the cracks are described based upon their location - crater cracks, root cracks, and heat-affected zone cracks are a few examples. Sometimes cracks are described based on their orientation with respect to the welding direction - longitudinal and transverse cracks being obvious cases. They may also be described by the nature of the problem that caused the crack- hydrogen-induced cracks, stress-relief cracks, etc. Reference 1 is a great source of information regarding welding terminology.

### Examination Procedure

The metallographer is often requested to examine a welded joint. To do this, they must cut out one or more specimens to sample the structure of the weld, heat-affected zone and adjacent base metal. Naturally, it is most convenient if all three regions can be contained within a single specimen. In many cases, welds are small enough to do this easily. But, in some cases, such as heavy plate welded by the electroslag process, the weld nugget alone can be quite large. Even here it is possible to prepare entire cross sections through the welds, although it is not as simple to do so as for smaller welds. The specimen is examined in the as-polished condition for voids of different types, such as porosity from gas evolution or shrinkage cavities, cracks that may be present in either the weld metal or the heat affected zone, regions where the weld did not exist (lack of fusion or lack of penetration) and for nonmetallic inclusions associated with the welding operation, chiefly slag-type in nature, in the weld or between weld passes (for a multi-pass weld).

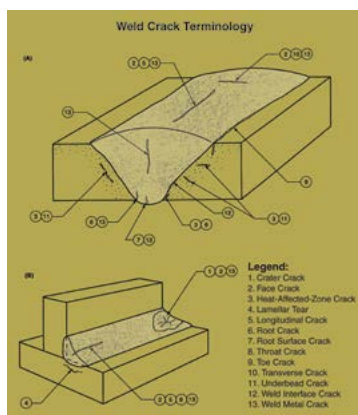


Figure 2. Terminology for describing cracks in welds (AWS A3.0: 2001 [1]).

### Obtaining and Preparing Weld Specimens

In some cases, the welded structure is large and, in the case of a field failure, a section must be removed by flame cutting. This process produces a substantial damaged zone adjacent to the cut, perhaps as wide as 10 - 15mm. When the section gets to the laboratory, the damaged cut region must be removed by a less-damaging cutting method, such as band sawing or abrasive sectioning. Then, the metallographer will cut out coupons using a laboratory abrasive cut-off saw that introduces less damage than production manufacturing equipment. Weld samples often tend to be large and irregular in shape. Many will not fit within a standard 1-, 1.25-, 1.5- or 2-inch (25-, 30-, 40- or 50mm) diameter mold for compression molding. In such cases there

are rectangular molds available that can accommodate these samples. Figure 3 shows a weld encapsulated using the 70mm x 40mm EPDM mold. EpoxiCure epoxy is highly recommended for these molds. Specimen holders are available for rectangular molds that enable automation of subsequent preparation procedures (Figure 4). In the event weld cross-sections are to be prepared without mounting one can cut the sample to dimensions that enable it to fit in the specimen holder directly.

When it is not possible to cut the samples to fit a specimen holder for rectangular samples, one can attach multiple weld samples to a blank specimen holder using double-sided tape or wax. This requires the samples are all cut very close to the same thickness so that grinding may proceed evenly.

Preparation procedures for ferrous metal welds are essentially the same as those for iron and steel though when samples are large more grinding may be necessary to plane samples prior to polishing. In such cases perform initial grinding using 180-grit CarbiMet, then follow the procedure in Table 1. Refer to the Buehler SumMet guide for further details on preparation of a variety of materials.

If the specimen is particularly difficult to prepare, it may be best to add a 1µm diamond step to the procedure, in the same manner as the 3µm diamond step, but for 3 minutes. For a holder with large specimens, the times may need to be increased.



Figure 3. Large welds can be encapsulated in epoxy using rectangular molds.

### Examination of Welds

Examination should always be performed after polishing and before etching to detect voids, cracks and inclusions. Then, the metallographer will etch the specimen to study both the macrostructure and the microstructure using an etchant appropriate for the alloy. In some cases, the weld metal is of sufficiently different composition that an etchant chosen to etch the base metal and heat affected zone will not reveal the weld metal structure, and vice versa, or one area may be badly overetched. If the specimen has been polished, the macrostructural details are usually adequately revealed by the etchant used to reveal the microstructure. In some studies, the metallographer will macroetch the specimen after grinding and study the macrostructure. This specimen is not suitable for microstructural examination, unless polished.

Most etchants used to reveal the microstructure of welds are standard general-purpose etchants. After examination with such an etch, it may prove to be valuable to use a color etching technique, as these can be far more sensitive for revealing grain structure, segregation and residual strain and deformation. However, these etchants are not widely used. Their use does require a very well prepared specimen for good results. But this level of perfection is easily achieved with modern equipment and consumable products. Figure 5 shows an example of the superiority of color etching over standard etchants in revealing the grain structure of a low-carbon steel weld.

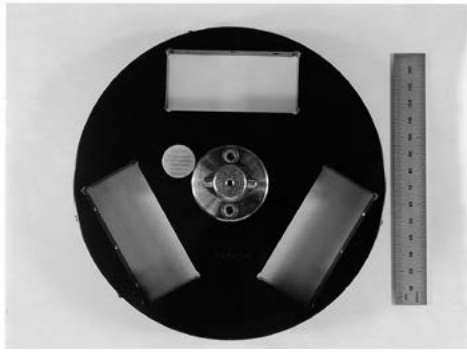


Figure 4. Example of a 7 inch (178mm) diameter specimen holder (for a 12 inch (300mm) diameter platen) with non-conventional openings for large rectangular specimens (1.375 x 3 inch or 35 x 76mm)

Both etchants revealed the as-cast structure of the weld metal, but the color etch was vastly superior in revealing the grain structure in the heat affected zone and base metal.

Figure 6 shows two low-magnification views of a fusion weld in AISI/SAE 1006 carbon steel etched with 2% nital and with Klemm's I tint etch. Nital does a good job, Figure 6a, revealing the transition from base metal to heat affected zone to weld metal. Note the black spots in the heat affected zone; these will be shown at a higher magnification revealing that they are fine pearlitic regions due to transformation of small regions that transformed to austenite, and contained all of the carbon in that area. These spots are not as easily observed in the color etch, Figure 6b. On the other hand, the color etch revealed the variation in grain size and shape far better than nital. Figure 7 shows the microstructure of the weld (a), heat affected zone (b) and base metal (c). Note that the base metal contained ferrite and grain boundary cementite films. In the heat-affected zone, where the black spots were observed, the temperature was high enough to locally dissolve the cementite into austenite, but there was insufficient time for the carbon content to become uniform. With cooling, these carbon-rich areas transformed to a pearlitic-like constituent. The weld structure is typical of a cast low-carbon ferritic grain structure with an acicular appearance and fine dispersions of cementite.

If a weld is given a post heat treatment, which does happen occasionally, the grain structure will be refined and the heat-affected zone will not be visible. As an example, Figure 8 shows the microstructure of Trimrite martensitic stainless steel (Fe - 0.23%C - 14.25%Cr - 0.65%Ni - 0.7%Mo) that was GTA welded and then heat treated (843 °C, air cooled, 788 °C, air cooled). Figure 8a shows the specimen etched with Vilella's reagent. The cast structure of the weld (255 HV) is clearly seen, but there is no heat-affected zone. The base metal (197 HV) is fine grained. Figure 8b, produced using Beraha's sulfamic acid etch (100 mL water, 3 g potassium metabisulfite, 2 g sulfamic acid and 1 g ammonium bifluoride), reveals the weld nicely and shows a grain size transition from the fusion line to the base metal where the HAZ was located. It is clear that the heat treatment refined the grain structure in the HAZ, but it is still coarser than in the base metal and the color etch reveals the transition in grain size from the fusion line to the base metal. This grain size variation was not as apparent with Vilella's reagent, at least not at this magnification (50X).

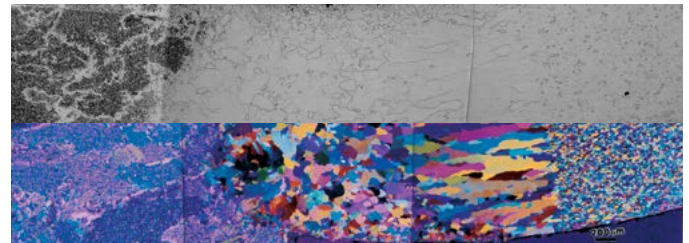


Figure 5. Example of a welded low-carbon steel etched with 2% nital (top) and Klemm's I (bottom) showing the clear superiority of color etching in revealing the grain structure. The as-cast weld metal is shown at the far left and the base metal is shown at the far right, above the  $\mu\text{m}$  bar. In between, we see the heat affected zone starting with coarse irregular grains adjacent to the fusion line, progressing to finer more uniformly shaped grains, then to columnar grains and finally to the very fine-grained equiaxed ferrite grains in the base metal.

Table 1. SumMet Method for Iron

Surface						
Sectioning	Abrasive Cutter with a wheel recommended for use on ferrous materials HRC15 -35					
Mounting	Compression or Castable, typically with EpoMet or VariDur 200					
Surface	Abrasive	Lubricant	Load - lbs [N]	Time (min:sec)	Platen Speed (rpm)	Rotation
CarbiMet	320 [P400] grit	Water	6 [27]	Until Plane	300	Comp
UltraPad	9 $\mu\text{m}$ MetaDi Diamond	NA	6 [27]	5:00	150	Contra
TriDent	3 $\mu\text{m}$ MetaDi Diamond	NA	6 [27]	3:00	150	Comp
MicroCloth	0.05 $\mu\text{m}$ MasterPrep Alumina	NA	6 [27]	2:00	150	Contra

Not all metals and alloys are easily color etched, however. Ferritic stainless steels are rather difficult. Thin-walled tubes may also be challenging subjects for the metallographer. Figure 9 shows an example of a welded thin-wall (0.015 inch, 0.38mm thick) tube of a "super" ferritic stainless steel, 29-4 (29% Cr - 4% Mo), that was electrolytically etched with aqueous 60% HNO<sub>3</sub> at 1.5 V dc. The weld is slightly thicker than the tube wall and we can see coarse grains with a dendritic structure that is reasonably equiaxed in the center but columnar in the outer regions of the weld. No obvious heat-affected zone is detected; hence, the tubing may have been annealed after welding.

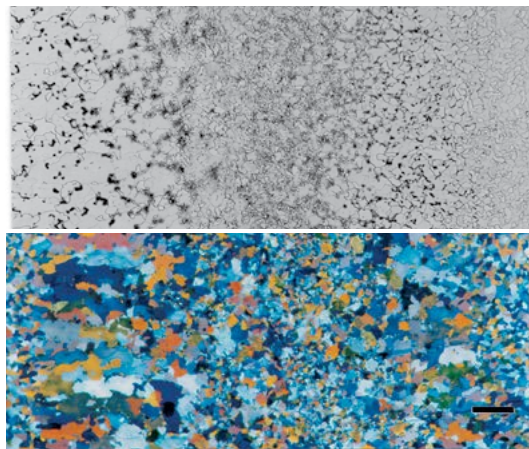


Figure 6. Low magnification view of a fusion weld in 1006 carbon steel revealed using 2% nital (top) and with Klemm's I (bottom) in polarized light plus sensitive tint (magnification bar is 200µm long).

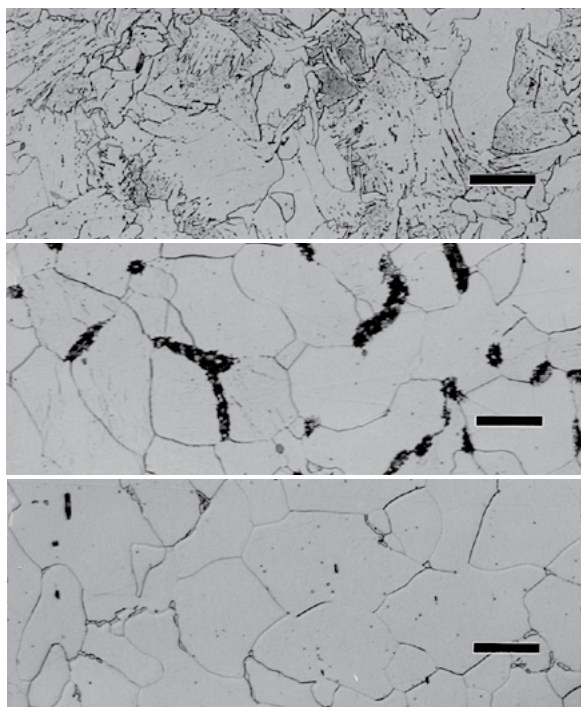


Figure 7. Microstructure of the weld (top), heat affected zone (middle) and base metal (bottom) of welded 1006 carbon steel etched with 2% nital. (Magnification bars are 20µm long).

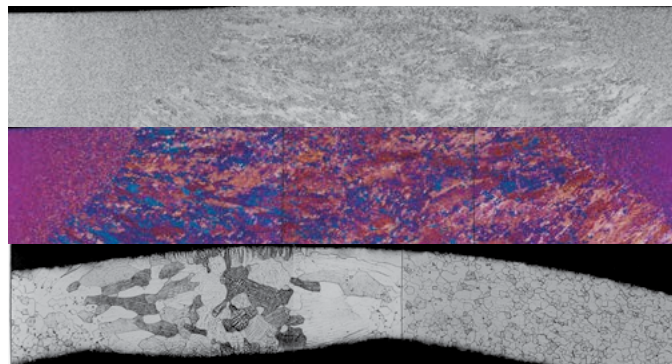


Figure 8. GTA welded Trimrite 1 martensitic stainless steel that was post heat treated and etched with Vilella's reagent (top) and with Beraha's sulfamic acid reagent (middle). The magnification bars are 200µm in length. Figure 9. (bottom) Microstructure of a thin-walled 29-4 (29Cr-4Mo) ferritic stainless steel etched electrolytically with aqueous 60% HNO<sub>3</sub> at 1.5 V dc (magnification bar is 100µm long).

## References

1. "Standard Welding Terms and Definitions," AWS A3.0:2001, The American Welding Society, Miami, Florida.
2. "SumMet - The sum of our experiences," Fourth Edition, Buehler, Lake Bluff, Illinois



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