# Metallography of Welds

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**Metallographic examination of weldments reveals macro-structural and micro-structural features clearly when good metallographic preparation and the right etchant are used.**

Welding is an important joining technology, and is highly dependent on the process choice, consumables used, operating parameters, and operator proficiency. Thus, inspection procedures, both nondestructive and destructive, are required to control the process and guarantee quality. Metallographic examination is a key tool in the destructive examination of weldments, both as a process control tool and as a post-mortem examination of failed components. Macrostructure must also be examined, which can be done on sections after grinding or polishing. Macrostructural examination is used to learn about the weld geometry, the depth of weld metal penetration, the magnitude of the heat-affected zone, and to detect cracks and voids. Microstructural examination is used to determine the mode of cracking and the cracking mechanism and to identify phases or constituents in the weld metal, heat-affected zone, and base metal including nonmetallic inclusions, as related to governing specifications, fitness for service, or cause of failure.

Many processes have been developed to produce welded joints such as the commonly used stick-electrode process that can be done in the field. Although welding is a comparatively new technology, forge welding predates by a large margin all other methods, as it dates from the earliest days of metalworking.

Brazing also has its roots in antiquity, mainly with jewelry production. Aside from forge welding, the other processes date from the 20th century, particularly since 1943 when inert-gas shielded welding was invented. Resistance welding of carbon steel was well established by about 1920, as it is less sensitive to metallurgical problems associated with fusion welding. Today, available processes include gas welding (and cutting) using an oxyacetylene flame; resistance welding, such as spot welding, induction welding, and flash welding; arc welding processes, such as gas-tungsten-arc (GTA), metal-inert gas (MIG), covered-electrode processes (stick electrode), submerged-arc welding, electroslag welding, electron beam and laser welding; and various friction welding processes. Many of these processes have been further modified in various 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 on the melting of the base metal to produce the joint.

## Weld terminology

Three main regions in welds are the base metal, the heat-affected zone (HAZ), and the weld metal (Fig. 1). Aside from the forge 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 essentially a casting. When wrought metal is welded, there is a temperature gradient, going from the nugget into 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 on the metals or alloys being joined. Using steels as an example, the weld nugget is created by molten metal (in many cases filler metal) that is heated in the arc until it melted.

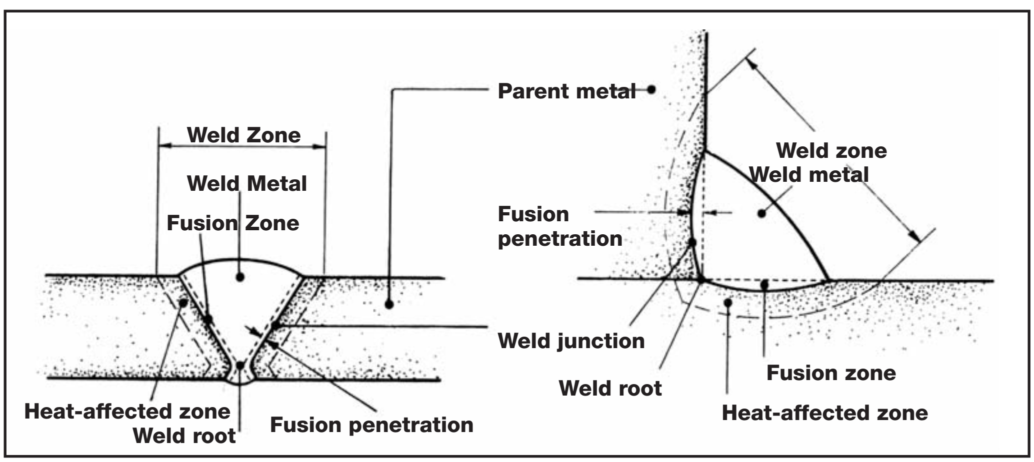


**Fig. 1 —** *Weldment terminology for a butt weld (left) and a fillet weld (right). Source: AWS A3.0: 2001.*

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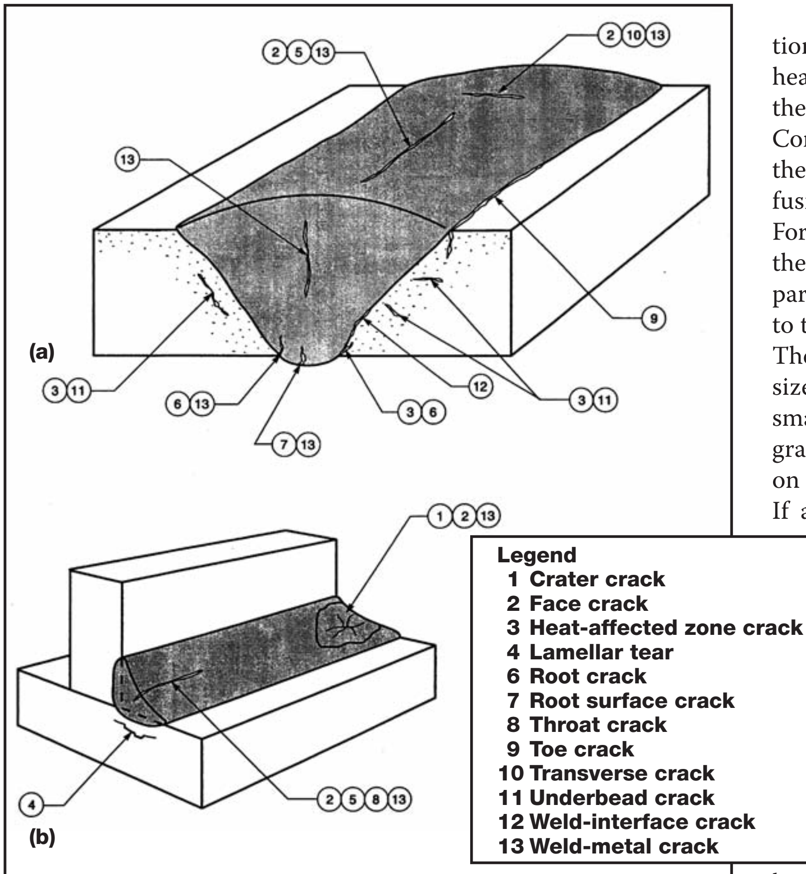


**Fig. 2 —** *Terminology for describing cracks in welds. Source: AWS A3.0: 2001.*

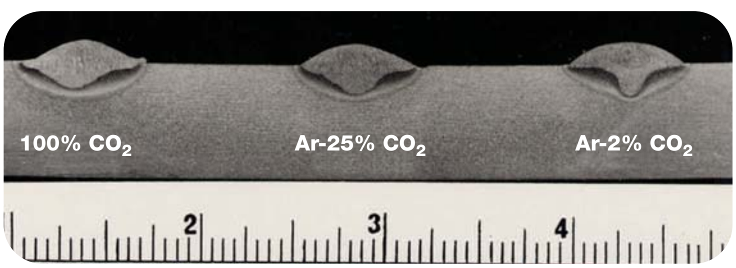


**Fig. 3 —** *Macrostructure of three GMA welds in a structural steel with a heat input of 45 kJ/in. and atmospheres of 100% $CO_2$, argon plus 25% $CO_2$, and argon plus 2% $O_2$. Etched with aqueous 10% nitric acid.*

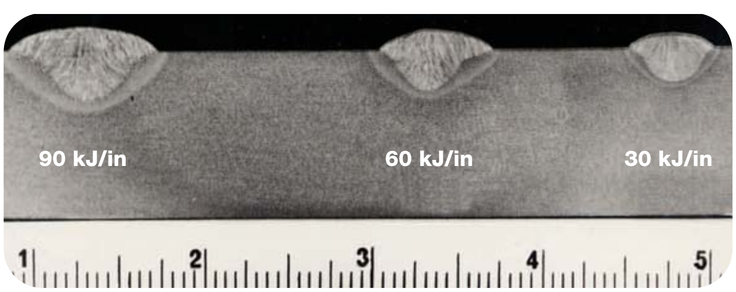


**Fig. 4 —** *Macrostructure of submerged arc welds in structural steel with heat inputs of 90, 60, and 30 kJ/in. (left to right); etched with aqueous 10% nitric acid.*

Solidification can occur under different cooling conditions, depending on the heat input, whether or not preheating or post-heating practices are used, depending on the mass of the pieces, ambient temperature, and so forth. Consequently, 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. For a carbon or alloy 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, $A_{c3}$, 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 on the temperature that they experience after nucleation. If a carbon steel was not deoxidized with aluminum, columnar grains might be seen. In the region of the HAZ that is heated into the two-phase $\alpha + \gamma$ field, the transformation on cooling could be quite different. For areas heated below the lower critical temperature, $A_{c1}$, the original structure might be tempered or might 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 might 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 on 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, such as longitudinal and transverse cracks. They may also be described by the nature of the problem that caused the crack; for example, hydrogen-induced cracks, stress-relief cracks, etc. Reference 1 is a good source of information regarding welding terminology.

## Macrostructural examination

The logical progression in examination is to examine the macrostructure before the microstructure. To do this, a section must be taken from the weldment, almost always transverse to the welding direction. The section can be smooth ground to a reasonably good finish using production machining equipment or metallographic preparation equipment. The author usually avoids using an "endless belt grinder," as the metal plate under the grinding belt often wears non-uniformly with use, which leads to non-planar surfaces. Grinding to the equivalent of a 600-grit SiC surface finish is adequate.

Macroetchants for steels cover a range of aggressiveness. The classic 1:1 $HCl:H_2O$ hot-acid etch at 160 to180°F


**Fig. 5 —** *To make measurements of weldment features using the Welding Expert, an etched surface is placed against the glass slide (as shown), the macrostructure is imaged on a computer screen, and the measurements are made.*

(70-80°C) for 15 minutes, or more (ASTM E 381) can be used, but cold acid etching is far more convenient. For steels, aqueous 10% $HNO_3$ or 10% ammonium persulfate have been commonly used. Both are reasonably safe to use. It is important to clean the ground surface properly before immersing the specimen in these solutions. Gentle swabbing can also be performed. Etching proceeds until the macrostructure is revealed with reasonable contrast and definition. The specimen is washed under running warm water, the water is displaced by squirting ethanol on the surface (avoid using methanol as it is a cumulative poison for humans), and dried using either compressed air or a warm air blast.

Figures 3 and 4 are examples of macroetched low-carbon structural steels welded using either different protective gas atmospheres or different heat inputs showing the influence of these variables upon the shape of the weld nugget, the depth of weld penetration, and the depth of the heat-affected zones. The structures were revealed using aqueous 10% nitric acid at room temperature. This technique is very useful for revealing weldment macrostructure. Figure 5 shows a device called the Welding Expert (Struers Inc., www.struers.com) used to measure key weld macrostructural parameters. An example of results for a typical fillet weld between two sections of carbon steel, ground to a 600-grit SiC finish and macroetched using 10% $HNO_3$ is shown in Fig. 6. Using the Welding Expert, vertical and horizontal lines are drawn in to define the edges of the horizontal and vertical legs of the weld, producing thickness measurements of 7.1 and 4.9 mm, respectively. Then, lines are drawn to the deepest penetration of the nugget into the horizontal and vertical legs, yielding 3.0 and 0.5 mm, respectively, for penetrations of 42 and 10%, respectively. It also is possible to draw horizontal and vertical lines to the depth of each heat-affected zone, or make other measurements, including angles.

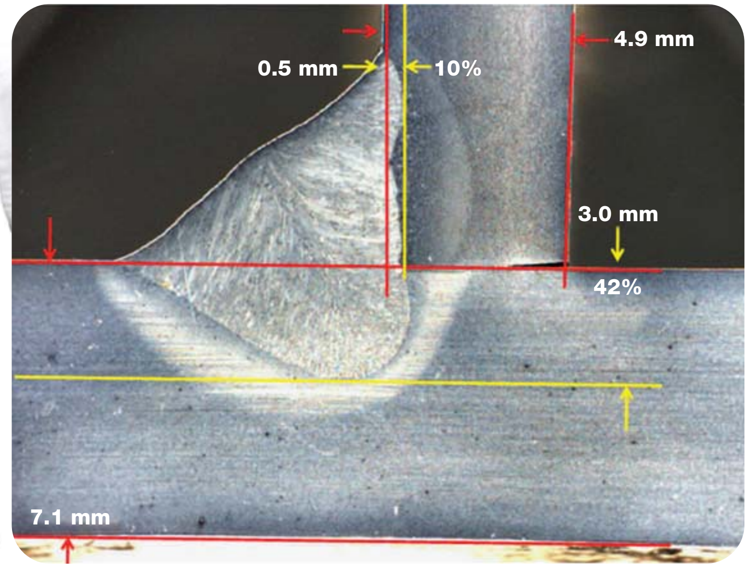


**Fig. 6 —** *An example of weld penetration depth measurements using the Welding Expert.*

## Microstructural examination

Metallographers often are asked to examine a welded joint. This requires cutting out one or more specimens to sample the structure of the weld, heat-affected zone, and adjacent base metal. It is 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 using 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 generally requires robust, large-scale grinder/polishers, such as the Abra System (Struers Inc.; www.struers.com). The specimen is examined in the as-

**TABLE 1 — METALLOGRAPHIC PREPARATION METHOD FOR STEELS**

| Step | Surface | DP | DP | OP |
|---|---|---|---|---|
| Surface | SiC paper | MD-Dur | MD-Dac | MD-Nap |
| Abrasive | SiC | DP-suspension | DP-suspension | OP-S or OP-AN |
| Grit Grain size | 120-220 | 9 µm | 3 µm | 0.04 or 0.02 µm |
| Lubricant | Water | Green or red | Green or red | |
| (rpm) | 240-300 | 120-150 | 120-150 | 120-150 |
| Force, N | 25 | 25 | 25 | 25 |
| Time, min | Until planar | 5 | 5 | 3 |

*Notes: For hard steels, MD-Allegro can be substituted for the SiC step. Alternatively, an MD-Piano 120 or 220 disc can be used rather than SiC. For soft steels or for ferritic and austenitic stainless steels, it may be desirable to add a 1-µm diamond step (similar to the 3-µm step) for best results.*

polished condition for different types of voids, 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).

Grinding and polishing cycles for welds differ little from procedures for non-welded metals and alloys. The major differences are that it might be necessary to polish an area that is larger than normal and that the hardness can vary across the specimen. That part of the specimen is a casting while the balance is wrought generally does not affect the preparation process. A practice suitable for many commonly welded ferrous alloys is presented in Table 1. Preparation methods for a wide variety of engineering metals and alloys are available from various sources, such as Struers Inc. The method in Table 1 can be easily modified to prepare Al, Cu, and Ni alloys.

A polished specimen, when etched using a suitable reagent for the alloy, reveals both the macrostructure and the microstructure. In some cases, the weld metal may be of a sufficiently different composition that an etchant chosen to etch the base metal and heat affected zone will not reveal the weld metal structure, or vice versa. Most etchants used to reveal the structure of welds are standard general-purpose etchants. After examination using such an etch, it might 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 requires a very well prepared specimen for good results. This level of perfection is easily achieved using

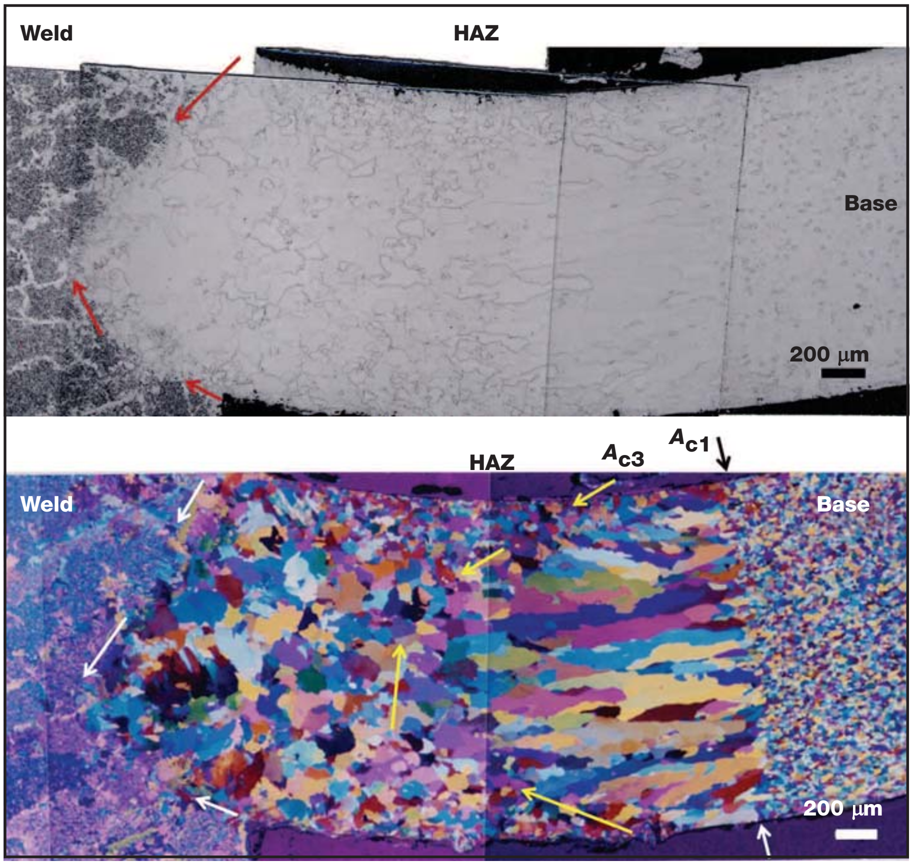


**Fig. 7 —** *Montage showing the structure of a large weld in a carbon steel revealed by 2% nital (top) and by Klemm's I (bottom) reagent (polarized light plus sensitive tint). The HAZ is larger than usual. Note that the grain size and shape change dramatically from the fusion line (red arrows at the top and white arrows at the bottom) to the base metal. The yellow arrows show the transition from columnar grain growth (for temperatures between $A_{c1}$ and $A_{c3}$ (yellow arrows) of a non-Al killed steel) and fine equiaxed grains for temperatures < $A_{c1}$ and for irregular, coarse equiaxed grains as the temperature increase above the $A_{c3}$.*

**Fig. 8 —** *Grain structure of a friction butt weld in Type 439 ferritic stainless steel etched using Beraha's sulfamic acid reagent (No. 4) and viewed using bright field illumination at 50×. The arrows point to faint strain lines in the weldment.*

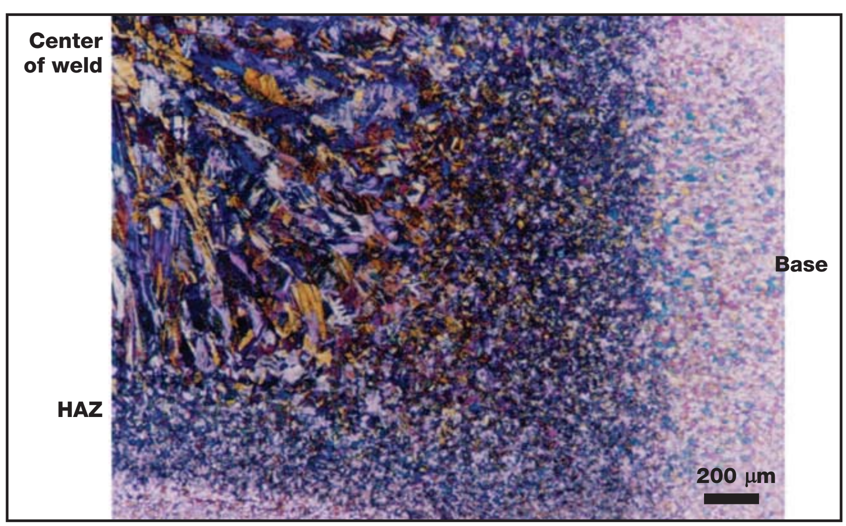


**Fig. 9 —** *Microstructure of a spot weld in a deep-drawing quality C-Mn sheet steel revealed using Klemm's I reagent and polarized light plus sensitive tint.*


**Fig. 10 —** *Microstructure of a spot weld (weld only) made between two 350-MPa HSLA steel sheets revealed by Beraha's sulfamic acid reagent No. 1 and viewed using polarized light plus sensitive tint.*

modern equipment and consumable products. Figure 7 shows an example of the superiority of color etching over standard etchants in revealing the grain structure of a low-carbon steel weld. Both etchants, nital and Klemm's I[2], revealed the as-cast structure of the weld metal, but the Klemm's color etch is vastly superior in revealing the grain structure in the heat-affected zone and base metal.

Ferritic stainless steels are rather difficult to etch, even when not welded. Figure 8 shows a friction butt weld (no filler metal used) between bars of Type 439 stainless steel where Beraha's No. 4 sulfamic acid etch[2] was used to clearly reveal the weld structure, heat-affected zone, and base structure. The arrows point to strain lines created by the frictional pressure.

Figure 9 shows an electrical-resistance (spot) weld between two sheets of C-Mn deep-drawing sheet steel using Klemm's I. Note the directional solidification pattern revealed fully by the color etch. In spot welding, the permanent electrodes are water cooled and the contact surfaces should not be melted. Melting should only occur between the two faying surfaces; that is, the contact region between the two sheets. Figure 10 shows an example of a spot weld (weld metal only) between two 350-MPa HSLA steel sheets using Beraha's sulfamic acid reagent No. 1. Both examples were imaged using polarized light plus a sensitive tint filter to enhance coloration. Figure 11 shows a friction stir weld in 2519 aluminum alloy with the grain structure beautifully revealed using Weck's reagent for Al[2]. Note the dark zone along the top edge due to the deformation produced by the friction stir tool. Figure 12 shows a braze using Ni-base Nicrobraze LM between K-Monel (left) and Type 304 austenitic stainless steel (bottom). Note the heavy carbide precipitation in both heat-affected zones.

## Conclusions

With good metallographic preparation, and the choice of the best etch, metallographic examination of weldments reveals macrostructural and microstructural features clearly with excellent image contrast. There is no substitute for a high-quality light microscope and a good imaging system. For macrostructural examination, color

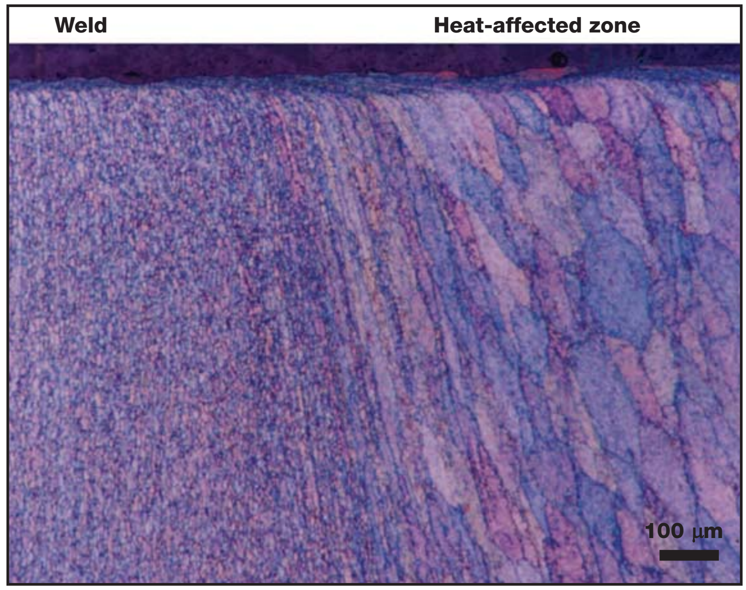


**Fig. 11 —** *Microstructure of a friction stir weld in 2519 aluminum alloy (Al - 5.8% Cu - 0.3% Mn - 0.3% Mg - 0.06% Ti - 0.1% V - 0.15% Zr) etched using Weck's reagent and viewed using polarized light plus sensitive tint.*


**Fig. 12 —** *Braze using Nicrobraze LM (Ni-7Cr-3Fe-3.1B-4.5S) between K-Monel (left) and Type 304 stainless steel (below). Note carbide precipitation (sensitization) in the heat affected zones. Etch: 14 mL water, 100 mL HCl, 3 mL $HNO_3$, and 20 g $FeCl_3$ dissolved in 20 mL water.*

etchants often provide results far superior to what can be accomplished using standard black and white etchants. Weld macrostructural features can be very important in judging the suitability of a weld for service, for determining conformance to specifications, and for diagnosing failures when they occur.

**References**

1. Standard Welding Terms and Definitions, AWS A3.0: 2001, The American Welding Society, Miami, Fla.
2. G.F. Vander Voort, ASM Handbook Vol 9: Metallography and Microstructures; Color Metallography, ASM International, Materials Park, Ohio, p 505, 2004.

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