JACQUET-LUCAS AWARD

NEW ETCHING TECHNIQUE FOR CHARACTERIZING FRICTION STIR WELDS IN ALUMINUM ALLOYS

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This entry won the prestigious 2017 Jacquet-Lucas Award for Excellence in Metallography at the International Metallographic Contest held during MS&T in Pittsburgh, October 2017.

Friction stir welding (FSW) is a solid-state welding technique developed to join various alloys[1,2] and components. For example, the automotive industry uses the technique to fabricate aluminum alloy tailor welded blanks (TWBs) used in the manufacture of automobiles. There is a demand for these components in various material thicknesses and alloy compositions. This requires a metallographic analysis method that enables thorough, rapid analysis of FSW joints to support R&D and keep pace with industry demand. This article discusses the development of a metallographic characterization technique to identify defects in the weld fusion area to enable fast optimization of weld processing conditions.

Defects in FSW joints have been examined using various methods[3]. However, most cross-sectional analysis techniques only allow examination of either grain structure and flow in the FSW stir zone or defects such as oxides in the joint. Oxides in the stir line can lead to lower strength values[4], so process optimization and tool design are used to prevent entrainment of oxides. However, the oxide line needs to be analyzed in conjunction with grain flow and grain structure to properly optimize the process. The authors developed an etching technique that reveals grain structure and grain flow and identifies lines of oxides, voids, and other exogenous materials on the same sample. Using optical microscope imaging, the etching technique reveals all of these microstructural features in one step for 5000 and 6000 series aluminum alloys. Results are based on examining samples produced using high-speed FSW with >2 m/min linear travel speed at TWB Co., Monroe, Michigan, with process parameters developed for cost-effective mass production of aluminum alloy TWBs. No data is presented for production FSW conditions and no welds from optimized production samples are shown due to proprietary restrictions.

EXPERIMENTAL PROCEDURES

Metallographic samples for cross-sectional examination were cut from welded blanks or blanks, mounted in epoxy, and resectioned using a high-speed precision saw. A small piece of aluminum was left protruding from the backside of the mount for easy electrical connection during etching. Grinding and polishing were done by hand. Final polishing was performed immediately before etching using 0.05-µm colloidal silica on a pre-wet (with water) low-nap synthetic polishing cloth at 150 rpm for 30 s. Samples were thoroughly washed with a micro-organic soap, rinsed with water, and transferred to the etching station immediately after rinsing. (Contact the corresponding author for more details on the sample prep procedure.)

All samples were etched using Barker's reagent (4% aqueous solution of fluoroboric acid, or HBF). The counter electrode was aluminum alloy 6111. Because all samples (one sample per mount) exhibited relatively consistent areas, current was not monitored and voltage was set at 20 V. Some samples were etched by submerging the polished face in the acid for 120 s with the voltage on. Others were etched using a modified procedure consisting of submerging in Barker's for 20 s with no voltage applied, then applying 20 V for 100 s. Samples were rinsed with flowing water, dried, sprayed with ethanol, and dried for at least 5 min in warm air prior to examination.

Optical microscopy was performed using an inverted metallographic microscope with polarized light and a full-wave (lambda plate) sensitive tint filter, which alters the polarization state of the light, producing color contrast between grains in the samples. The level of polarization prior to entering the lambda plate was varied. Images were captured using a digital camera.

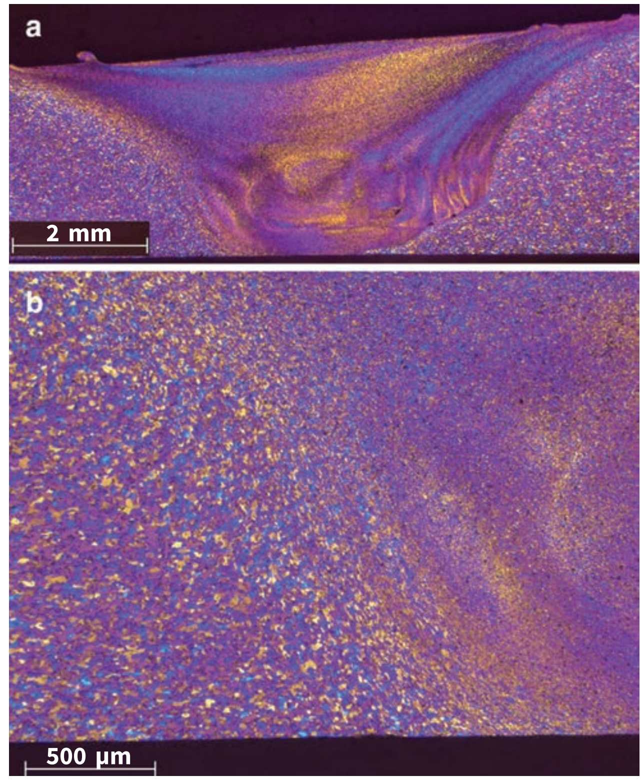

Fig. 1 — Optical micrographs of a friction stir butt-weld joint fabricated with two aluminum alloy 5754 sheets of dissimilar thickness, etched with Barker's reagent following standard procedures where voltage is applied immediately: (a) image of the entire FSW stir zone, magnification 12.5x; and (b) transition from parent metal to stir zone at the weld root, magnification 50x.

RESULTS AND DISCUSSION

Figure 1 shows a cross section through a friction stir butt weld of two pieces of AA5754 of different thicknesses etched with voltage applied immediately after submerging the sample into the solution. Grain flow contrast (Fig. 1a) and grain definition at the weld root transition from the parent metal to the stir zone (Fig. 1b) are excellent, but it is difficult to see the oxide stir line. After significant trial and error in seeking a satisfactory modification to the etching technique, it was determined that the optimal method was to submerge the sample in the etchant for 20 s prior to applying voltage. Shorter times did not provide significant contrast for the oxide line, and longer times pitted the precipitates in the microstructure more severely (although there is still some limited pitting of the precipitates using the optimal time as well).

Figure 2 shows a cross section through a developmental AA5754 weld containing an oxide line and voids. Figure 2(a), using fully cross-polarized light and the lambda plate inserted, provides grain flow and grain structure/size information, and clearly delineates the oxide stir line. Reducing the level of polarization below fully cross polarized makes the oxide line stand out, and it is clearly observed in the microscope (Fig. 2b). This technique enables collecting a significant amount of information from one sample, which can be used to make process modifications and quickly optimize the process to eliminate voids and oxide lines.

The etching technique is also useful during FSW process development to characterize the failure of samples subjected to mechanical testing. Mechanical testing was performed using a limiting dome height (LDH) tester. When a sample with dissimilar thickness blanks was tested, an aluminum shim was used in the LDH tester to prevent uneven loading. A fluoropolymer film was used for lubricity between the punch and the welded blank in all LDH testing.

A micrograph of a friction stir weld in AA5754 that has undergone LDH mechanical testing is shown in Fig. 3. The test was conducted with the bottom (root) of the weld up, which is similar to the intended forming direction on this part, to determine if voids or the oxide line influences the location of the fracture. The image was taken with polarization and color tint reduced to highlight the oxide line. While voids are present near the weld root at the peak of the dome, the oxide stir line is the location where fracture initiated.

Figure 4 shows a friction stir butt weld made using two pieces of AA6111 of the same thickness. Excessive dry film lubricant was applied to the surfaces of the Al alloy sheets to determine whether it would reduce friction-generated heating or have any other negative influences on the weld. The oxide line at the interface of the two aluminum sheets was not broken up well, but a substantial amount of the lubricant was incorporated on the advancing side (right side) of the FSW stir zone (Fig. 4a). Figure 4(b) shows the lubricant in the stir zone at higher magnification. The etching technique is useful in

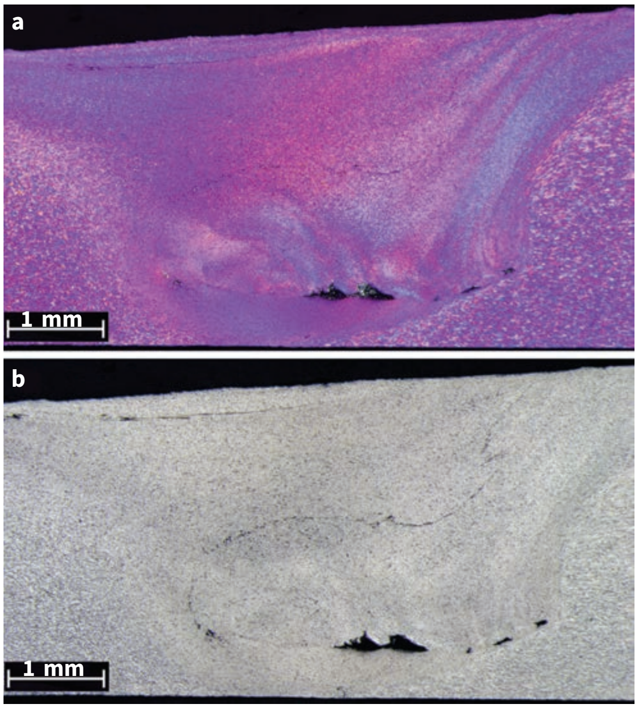

Fig. 2 — Optical micrographs of an etched friction stir butt-weld joint of AA5754 of dissimilar gauges: (a) image collected with cross-polarized light and lambda plate shows grain flow and grain structure/size information, and clearly delineates the oxide stir line, magnification 25x; and (b) same region with polarization moved slightly away from the fully cross-polarized condition and lambda filter slightly reduced clearly shows oxide line.

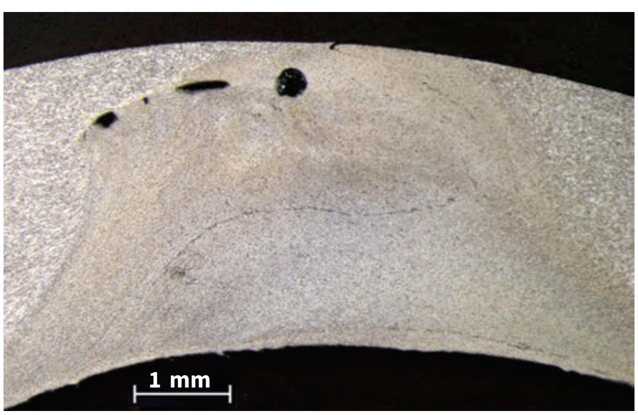

Fig. 3 — Micrograph of a friction stir welded AA5754 sample containing voids and an oxide line subjected to mechanical testing using the limiting dome height (LDH) method with root side up (away from the ball). Etching shows that the oxide line was the origin of the fracture, magnification 25x.

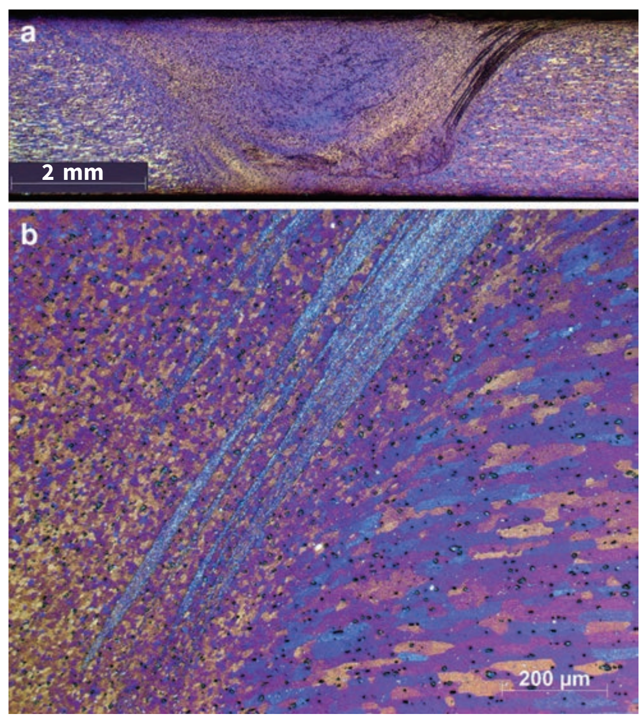

Fig. 4 — Micrographs of a sample of friction stir welded AA6111 sheets of same thickness made with excessive dry film lubricant on their surfaces: (a) oxide line present at the center of the joint and lubricant incorporated into the joint; and (b) lubricant in the stir zone shown at higher magnification, 100x.

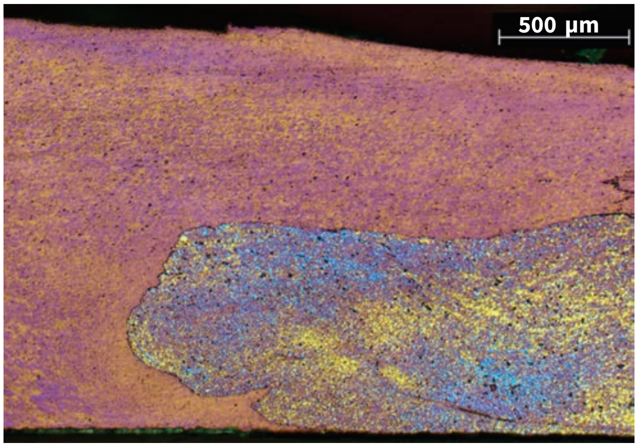

Fig. 5 — Micrograph of friction stir welded AA6022 (left) and AA5182 (right) sheets of different thicknesses, magnification 50x. Etching reveals a clear oxide line at the weld interface and additional oxide lines in alloy 5182 near the weld root and in alloy 6022 near the weld face (far right side).

determining the upper limit of dry film lubricant weight applied to sheets for the FSW process.

This etching technique is also useful for examining welds between dissimilar alloys. Figure 5 shows the bond line in a developmental friction stir weld between aluminum alloys 6022 and 5182 made using less than optimal conditions. Oxide lines (at the 6022-5128 interface and in 5182) and differences in grain structure are clearly visible. **~AM&P**

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