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Microstructure and Strength Characteristics of Friction Stir Welded 2139 Aluminum Armor

ABSTRACT

The friction stir welding (FSW) process is increasingly being applied to new metal alloys which often emanate from the needs of the military defense industry. Of particular interest to military vehicle designers are the newly developed aluminum alloy armors which provide a weight reduction benefit relative to traditional steel armor materials without the lower strength limits of older aluminum alloys. However because of the high strength and hardness characteristics of these alloys, the application of conventional fusion welding processes to them is often difficult. FSW is a solid-state process that provides the significant benefit of being able to join metals which are difficult and sometimes impossible to weld with fusion techniques. A further benefit of the FSW process when applied to aluminum alloys is a lower reduction of material strength at the weld joint compared to that of a fusion welded joint of the same material. For this study, we have optimized the FSW process parameters of 2139 aluminum alloy (Al-5%Cu) and analyzed the microstructure and strength characteristics using a scanning electron microscope (SEM), an electron backscatter diffraction system (EBSD), microhardness mapping, and tensile tests. Our results confirm that FSW is an applicable method of welding 2139 aluminum alloy which provides the benefits outlined above.

INTRODUCTION

After the advent of friction stir welding in the early Nineties, this manufacturing process was soon adopted by the aircraft and aerospace industries for use in joining aluminum components. The prime benefit being that this solid state welding process yielded higher joint strength relative to joints created by the matured and more commercially viable fusion welding methods. Due to the high temperatures and heat inflicted on an aluminum joint during a welding process, the mechanical strength characteristics of the material within the heat affected zone (HAZ) are substantially degraded relative to the unaffected base material. For example the ultimate yield strength of a gas metal arc weld (GMAW) joint in 5083 aluminum is 24 ksi[1] which is approximately 40% weaker than the base material (46 ksi[2]). However a FSW joint of this material is only 12% weaker than the base material and 69% stronger than an equivalent GMAW joint[3].

As development of aluminum alloy compositions has improved, metallurgists have been able to significantly improve the strength and wear resistance capabilities of these alloys. Unfortunately these gains have come with the loss of weldability and

[1] American Welding Society, Welding Handbook Vol. 3, 1996, p. 101
[2] Ibid, p. 8
[3] Focus Hope Industries, 2011

increased complexity of fusion welding parameters. Depending on the alloy class and chemical content, to avoid post weld cracking, fusion welders often need to acutely balance several process parameters including filler metal selection, pre-heating, in-process heat, and travel speed. Because the FSW process controls heat input and maintains material temperatures significantly below an alloy's modulus point temperature, the material within the weld joint's heat affected zone (HAZ) remains in either a solid or plastic state. The susceptibility to heat-induced cracking is thus mitigated.

Aluminum alloy 2139 (Table 1) is increasingly being selected for structural designs which require strength and hardness yet seek to minimize system weight specifically exterior weldments of military vehicles which are susceptible to ballistic impacts. This investigation conducted a Taguchi design of experiments study to determine the optimum FSW process parameters for 1-inch thick 2139 aluminum alloy and then analyzed the microstructure and mechanical strength of the resulting stir zone material.

Table 1 - Elemental Composition of AA2139

Element	%
Silicon	0.1
Iron	0.5
Copper	4.5 - 5.5
Manganese	0.2 - 0.6
Magnesium	0.2 - 0.8
Chromium	0.005
Zinc	0.25
Titanium	0.15
Vanadium	0.05
Silver	0.15 - 0.6
Other	0.15
Aluminum	remainder

FSW Parameter Optimization

For this study, a work piece fixture (Figure 1) that would securely constrain two 1-in. x 2-in. x 8-in. material bars was fabricated and mounted to the work surface of a Transformation Technologies, Inc. Model GG1 FSW machine. Based on prior experience with 1-inch thick aluminum alloy, we selected an FSW tool constructed of H13 tool steel with a scrolled pin and shoulder (Figure 2).

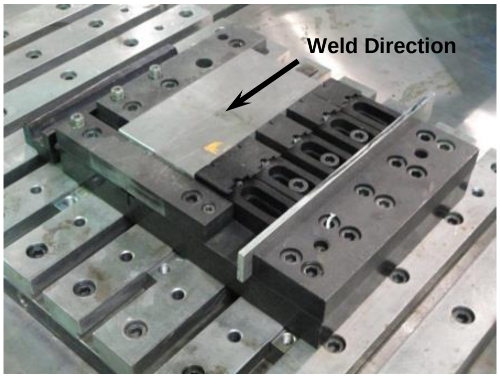

Figure 1: Coupon Weld Fixture

Figure 2: FSW Tool

The 2139 aluminum armor used for this project was manufactured by Alcan Rolled Products (Ravenswood, WV). Due to the limited availability of this experimental armor, it was delivered as three large plates: one 1-in. x 24-in. x 47.5-in. (Lot #820081) and two 1-in. x 48-in. x 48 in. (Lot # 820091). The plates were cut into 2-in. wide bars using a water-jet machine and these bars were then cut into 8-in. lengths using a band saw with cooling fluid. One side of each bar was milled to remove the surface finish left by the water-jet cutting process.

The weld coupons were all manufactured on the same FH-CAT FSW machine, a Transformation Technologies, Inc. (Elkhart, IN) Model GG1, in single batches for each material.

As preparation for X-ray inspection of the welds, both ends of the coupons were removed using a laboratory precision wet saw to remove the weld start and exit holes and to set the final coupon lengths of 4.5-in. The top and bottom faces of each coupon were then milled to remove weld flash. Each coupon was then X-ray inspected at Magna Chek Inc. (Madison Heights, MI). None of the coupons exhibited any internal flaws.

WELD JOINT METALLURGICAL ANALYSIS

After the material-specific FSW process parameters were optimized, a set of coupons was segmented using a laboratory wet saw to provide transverse weld joint samples for hardness evaluation, micrographs, scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and tensile strength analysis. As required, samples were mounted, polished, and/or chemical etched (Keller's reagent). The transverse tensile test specimens (ASTM E8 – flat, sub-size) were machined and tested at FH-CAT (See Figure 3).

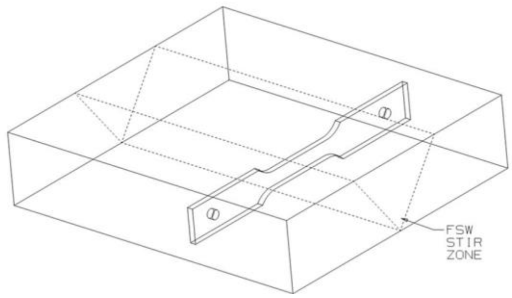

Figure 3: Tensile Test Specimen Location

Microstructural analysis was conducted using a Nikon Eclipse LV150 optical microscope and a Zeiss EVO MA10 SEM. Images were obtained from the optical microscope using a calibrated digital camera, and Scentis software. Optical microscope images were captured at 500x magnification and SEM images were captured at 500x and 1000x magnifications.

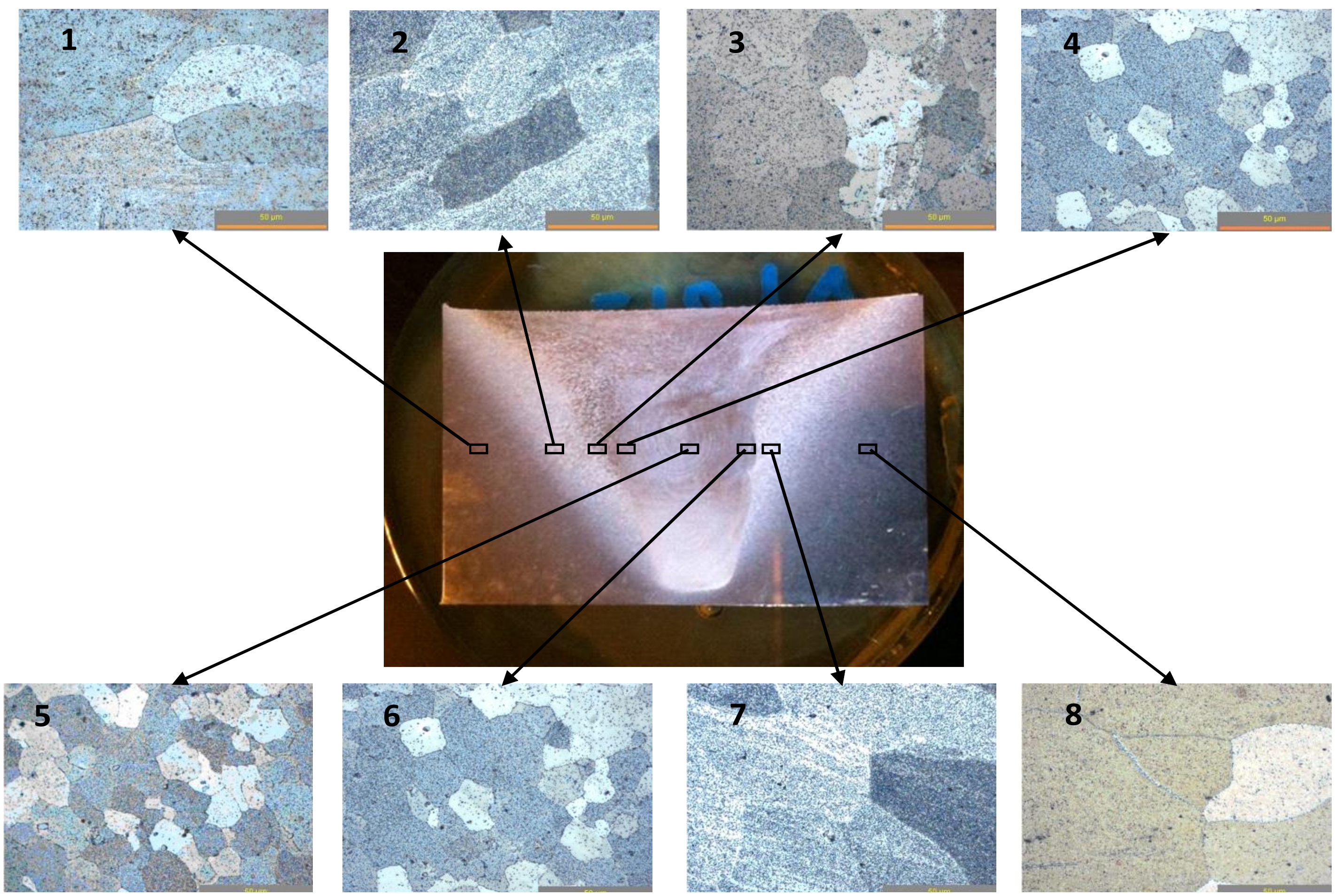

Figure 4: Microscopic Views of 2139 FSW Joint.

Further definition of the metallurgic grain structure across the weld joint was conducted using EBSD. Prepared FSW joint samples were analyzed with a Hikari/EDAX backscatter detection system mounted to a Zeiss EVO MA10 SEM.

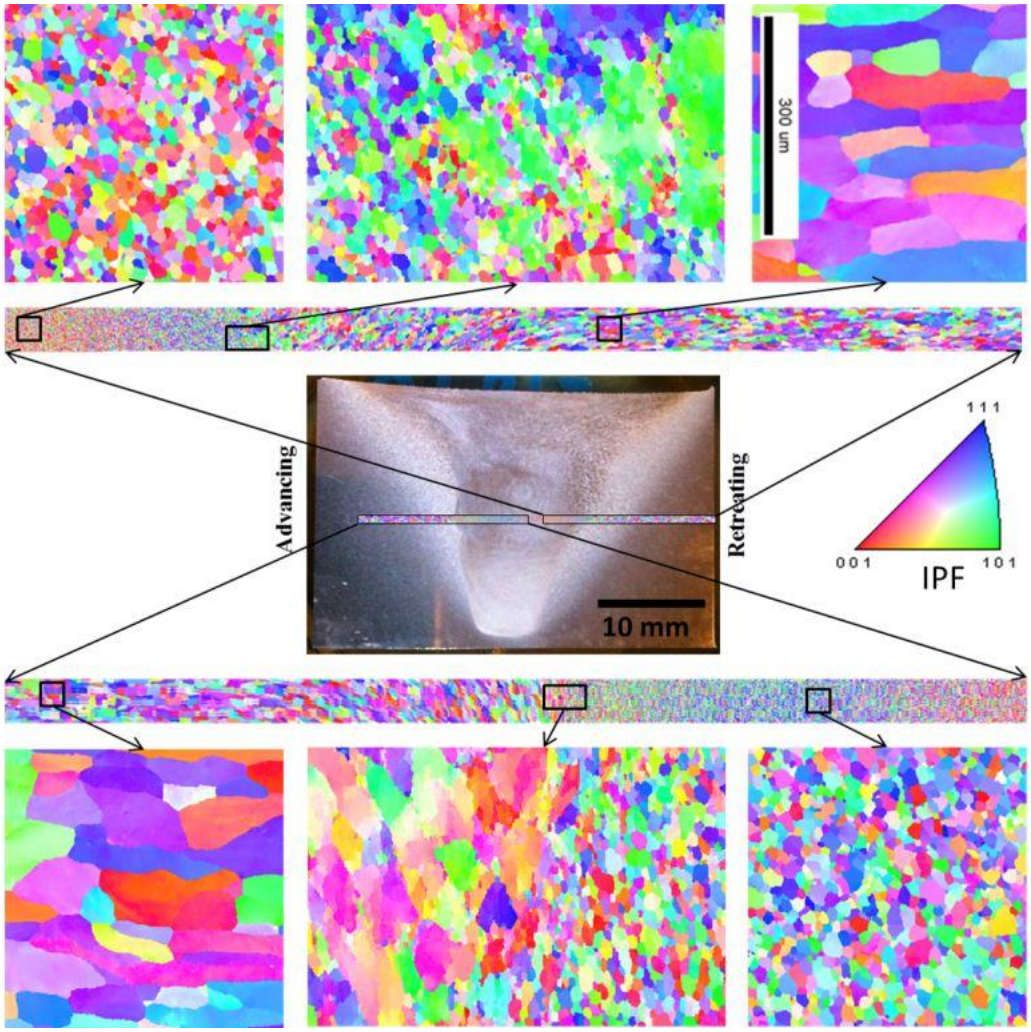

Figure 5: EBSD of 2139 FSW Joint

MECHANICAL TESTS

Micro-hardness charts were created using a Leco LM100AT hardness tester. The resulting micro-hardness profile shown in Figure clearly depicts the characteristic V shape of the thermo-mechanically affected zone (TMAZ) of a friction stir weld. The apparent asymmetry distinguishes between the advancing and retreating sides of the weld.

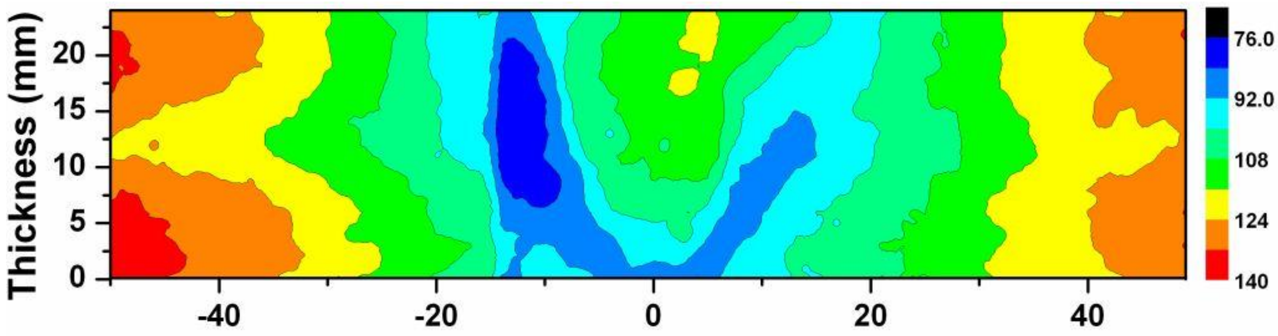

Figure 6: FSW Joint Micro-Hardness (HV)

Tensile tests were conducted using an Instron Model 5982 universal testing machine with a strain rate of 1 mm/min. The force was measured using a 100 kN load cell, and elongation was measured using a 1-in. length extensometer. Table 2 compares the strength test results with the un-welded base material. Figure 3 depicts the stress vs. strain relationships of the AA2139 FSW joint.

Table 2 : Tensile Test Results

Material	Yield	UTS	Elongation
AA2139-T8 base material	475 MPa	509 MPa	13.1%
AA2139 FSW (as-welded)	235 MPa	405 MPa	14.9%
AA2219-T81 GSAW (as-welded)[4,5]	179 MPa	241 MPa	3%

[4] As AA2139 is considered an un-weldable alloy, by gas shield arc welding (GSAW) methods, the weld strength of AA2219 using AA2319 filler is provided for comparison.
[5] American Welding Society, Welding Handbook Vol. 3, 1996, p. 105

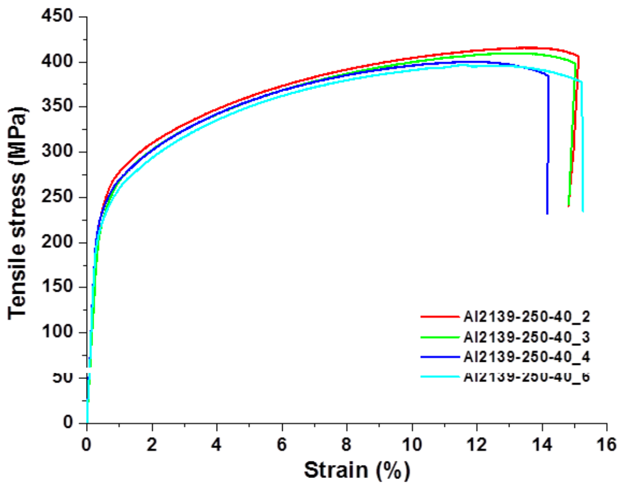

Figure 7: 2139 FSW Stress vs. Strain

SUMMARY

The tensile strength of the friction-stirred AA2139 was reduced by 50% from the base material strength. However a typical fusion-welded joint for this material loses 62% of its strength which indicates that friction-stir welding is a better choice for joining this material. Microstructural analysis shows that the central Stir Zone of the friction-stirred joint exhibits smaller, refined grain size than the base material because of dynamic recrystallization caused by the severe plastic deformation that occurs when the stir tool passes through the metal. While this phenomenon typically creates stronger material, the overall tensile strength of a transverse test specimen is limited to the weakest part of the friction stir joint, which is the TMAZ. The micro-hardness profile of the joint indicates that the softest material, and thus weakest, is found in the TMAZ. This material does not undergo recrystallization, but because of the elevated material temperatures caused by the process, alloy precipitates within this zone are dissolved which weakens the structure.

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