INVESTIGATION OF LAZY S FEATURE IN SELF-REACTING TOOL FRICTION STIR WELDS

Karl Warsinski[1], Michael West[2], Jim Freeman[3], Todd Curtis[2]

[1]Department of Materials Science and Engineering
Michigan Technological University

[2]Advanced Materials Processing and Joining Laboratory
South Dakota School of Mines and Technology
501 E. St. Joseph St., Rapid City, SD 57701 USA

[3]MTS Systems Corporation
14000 Technology Drive Eden Prairie, MN 55344 USA

Keywords: Friction stir welding; Self-reacting tool; Defects; Lazy S

Abstract

The current research is an examination of the “Lazy S” feature found in self-reacting tool (SRT) friction stir welds. The research objectives are to characterize the feature using scanning electron and optical microscopy and determine its effect on the mechanical properties of the welded material. Welds were conducted in 2024-T4 aluminum. Welding parameters were varied in an attempt to influence the size and location of the feature. Tensile tests were performed on each weld and were correlated with the total length of the feature. Preliminary results indicate that there is a correlation between decreasing feature length and decreasing tensile strength.

Introduction

The specialized fixture requirements of conventional friction stir welding limit the versatility and application of the process. Self-reacting friction stir welding tools should help to make friction stir welding practical for a wider range of applications. To that end, it is important to thoroughly understand any differences in material properties between conventional FSW and self-reacting tool welds, with particular regard to defects unique to the FSW process. In conventional friction stir welding, the material being welded flows not only around the sides of the pin, but below it as well. This is not possible with a self-reacting tool, because the pin penetrates completely through the welded material, presenting a different flow pattern and the potential for differences in defect formation.

While self-reacting friction stir welds are very similar to conventional friction stir welds due to the very nature of the process, the addition of a second shoulder and a full-thickness pin introduce the possibility of distinctly different characteristics. So far, there has been relatively little research published regarding the effect of these elements on the properties of friction stir welds. In order for self-reacting tools to be widely applicable in industry, any unique qualities of such welds must be investigated and understood both theoretically and practically.

Experimental

The purpose of this study was to produce SRT welds that exhibited the Lazy S defect in order to characterize its presentation when produced by a self-reacting tool. A low spindle speed was used, as a prior study suggested that this might promote formation of the Lazy S feature [1]. Several welds were made with the pin centered on the faying line between plates, and two welds were conducted with the tool offset to the advancing side of the weld, again to promote the formation of the Lazy S feature [2]. One “bead-on-plate”-type weld was performed as well.

Friction stir welding was conducted using the MTS ISTIR 10 system. Materials used in the experiments were 2024-T4 Al, received as 9.5 mm thick plates. Friction stir welds were executed in force control mode, and the faying surfaces of the plates were left in the as-received condition. Rotational speed of 230 RPM and a travel speed of 20.3 cm/min were used. The tool used had a 1.11 cm pin diameter and 2.54 cm shoulder diameter. The pin was grooved and had a quad-flat cross section, while the shoulders were scrolled inward, as shown in Figure 1A.

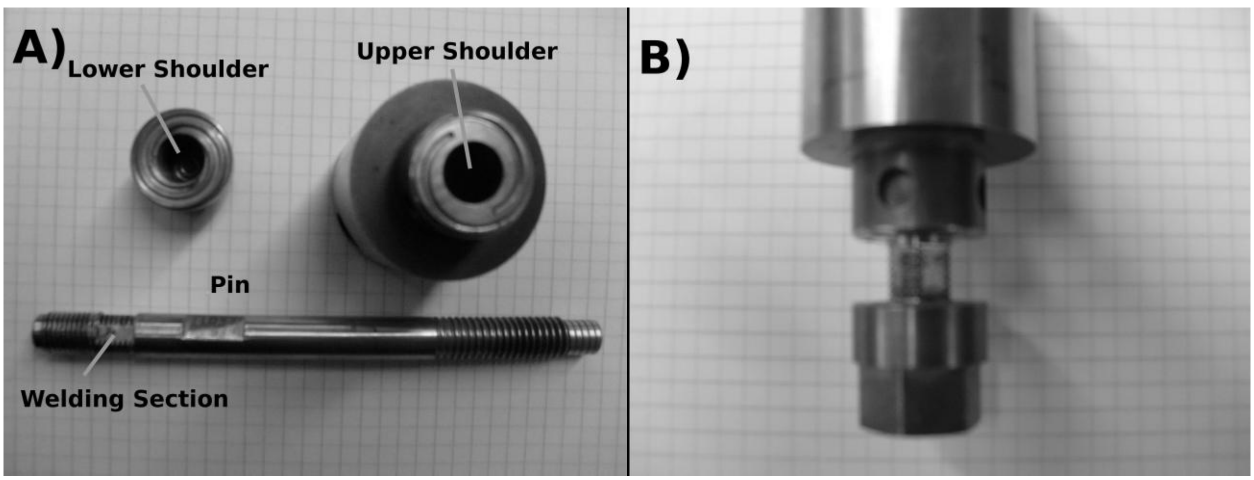

Figure 1. A) Sections of self-reacting tool, and B) Assembled tool.

Welds were sectioned and samples for optical and SEM microscopy were prepared, along with sub-size samples for tensile testing [ASTM]. Samples for metallographic inspection were polished, macro-etched with a 10% NaOH solution, lightly re-polished, then micro-etched with Keller's (7m) Reagent [4]. Optical microscopy was used to examine the microstructure, identify the Lazy S feature, and capture images for comparison. The images captured were used to measure the path length of the feature. Three tensile tests were performed on each weld. SEM and EDS analysis was carried out using a Princeton Gamma-Tech SEM operated at 10 kV.

Results and Discussion

The Lazy S feature was observed in all samples where two plates were joined. In most of the welds produced in this study, void defects were observed along the advancing side of the tool, clearly depicting the pin profile, as can be seen in Figure 2A. It is believed that this was caused by the low spindle speed which led to a decrease in plastic deformation. In some welds, clamping issues were observed which may have contributed to this phenomenon. Figure 2B shows the weld with the greatest offset (2.4 mm), which exhibits a noticeably straighter Lazy S configuration than the centerline welds. It was this observation which prompted the decision to measure the feature path length for comparison against tensile strength of each weld.

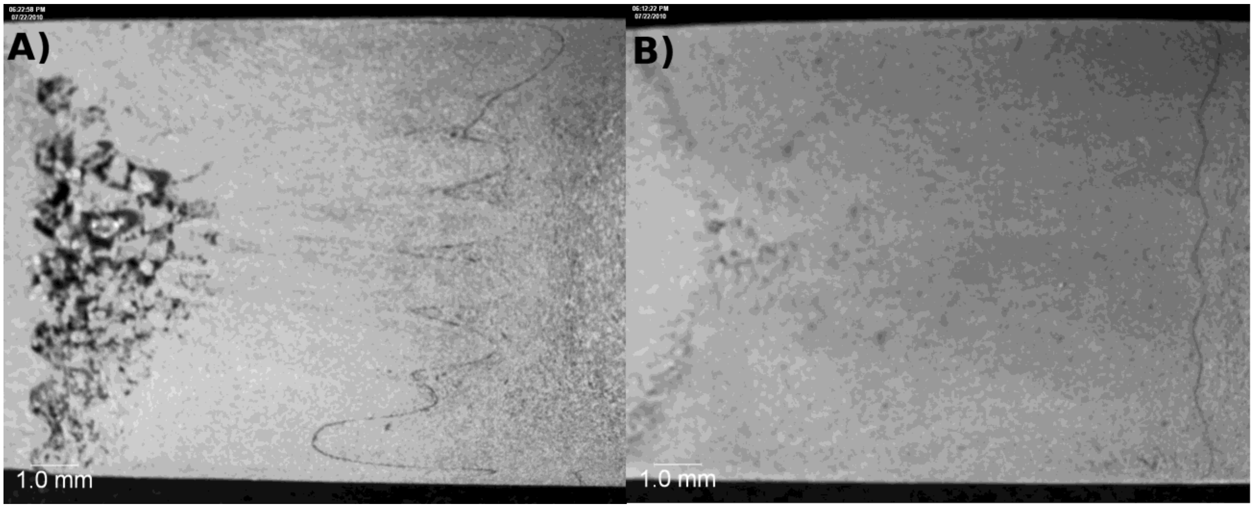

Figure 2. Macrograph showing A) a typical centerline weld, and B) weld with 2.4 mm offset to retreating side. Note that the advancing sides are on the left, and the Lazy S features can be seen on the retreating sides, on the right.

Tensile data for each weld was collected, and is shown in Table I, along with the measured path lengths of the corresponding Lazy S features (Welds SRT-1 and SRT-2 were not part of this study). While number of welds completed during this study does not provide sufficient data for full statistical analysis, the data available seems to indicate a relationship between feature geometry and the bonding strength of the weld along the feature.

Table I: Weld Properties

Weld ID	Tool Offset (Advancing side)	Average Yield Stress (MPa)	Feature Length (cm)	Break Position in Weld
Parent Metal	N/A	440	N/A	N/A
SRT-3	Centered	207	3.05	Void Defect
SRT-4	Centered	228	3.56	Void Defect
SRT-5	Offset 2.4 mm	117	1.02	Lazy S
SRT-6	Centered	188	2.54	Void Defect
SRT-7	Offset 1.2 mm	254	2.29	Void Defect
SRT-8	N/A*	288	None	Void Defect

* Weld SRT-8 was the bead-on-plate weld

As indicated in Table 1, and illustrated in Figure 3, the Lazy S feature was not observed in the bead-on-plate weld. While the micro-structure forms similar patterns on the retreating side of the weld, the same etching method did not produce the distinctive line present on the other samples. This supports the hypothesis that only the faying surface contributes to formation of the Lazy S feature.

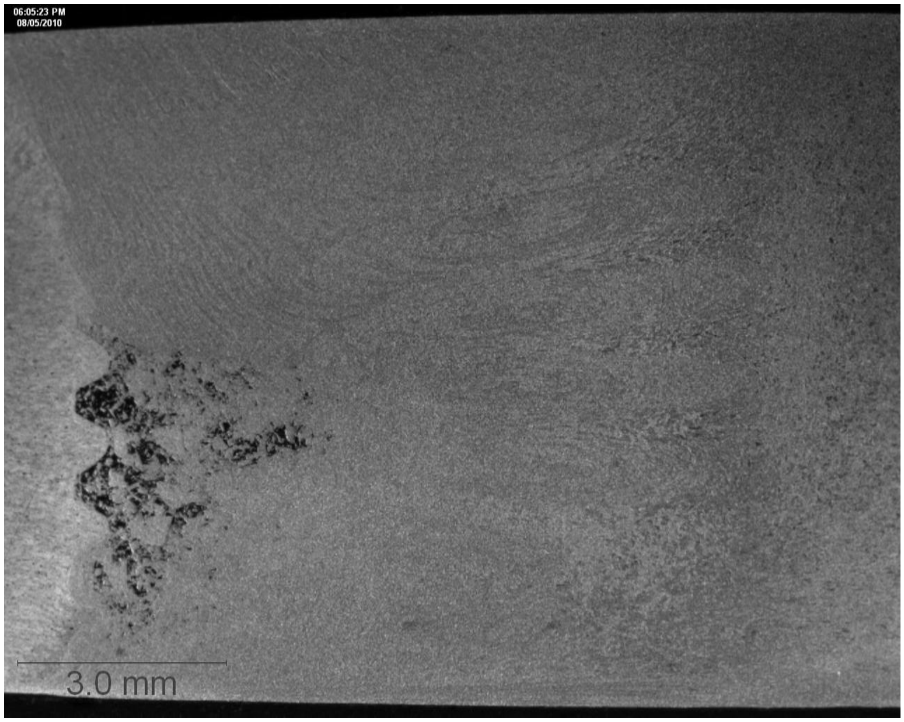

Figure 3: Micrograph of bead-on-plate style SRT weld. The advancing side of the weld is to the left, and again shows a void defect.

The SEM was used to examine the fracture surfaces of two tensile samples, one from SRT-4 and one from SRT-5. Figure 4 shows a portion of the SRT-4 fracture surface that experienced ductile failure. This area was located along the advancing side of the nugget, above the void defect. Figure 5 shows the brittle fracture surface of SRT-5, along the Lazy S feature.

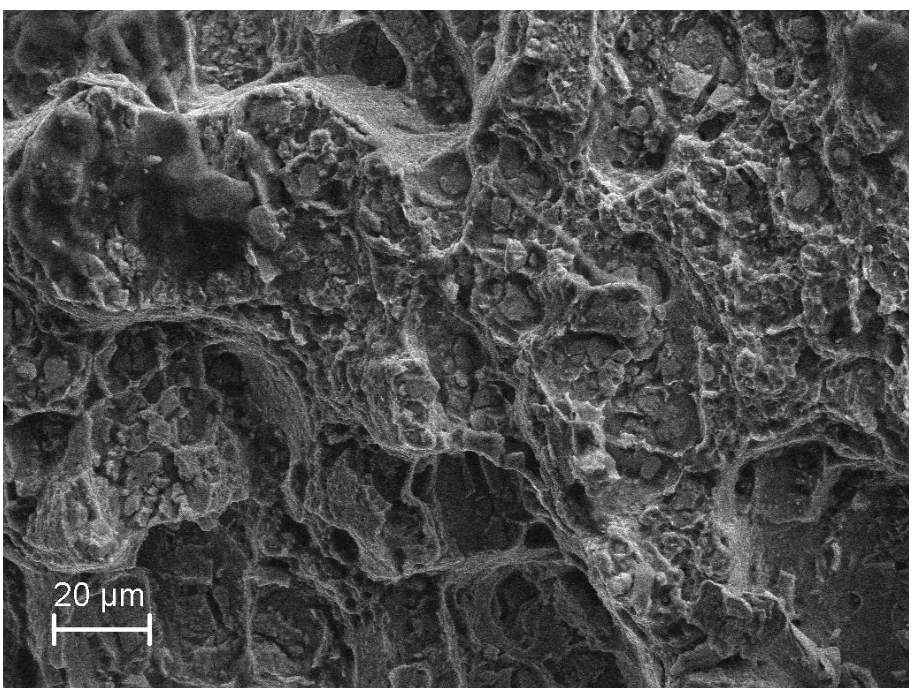

Figure 4: SEM image of SRT-4 fracture surface through weld nugget.

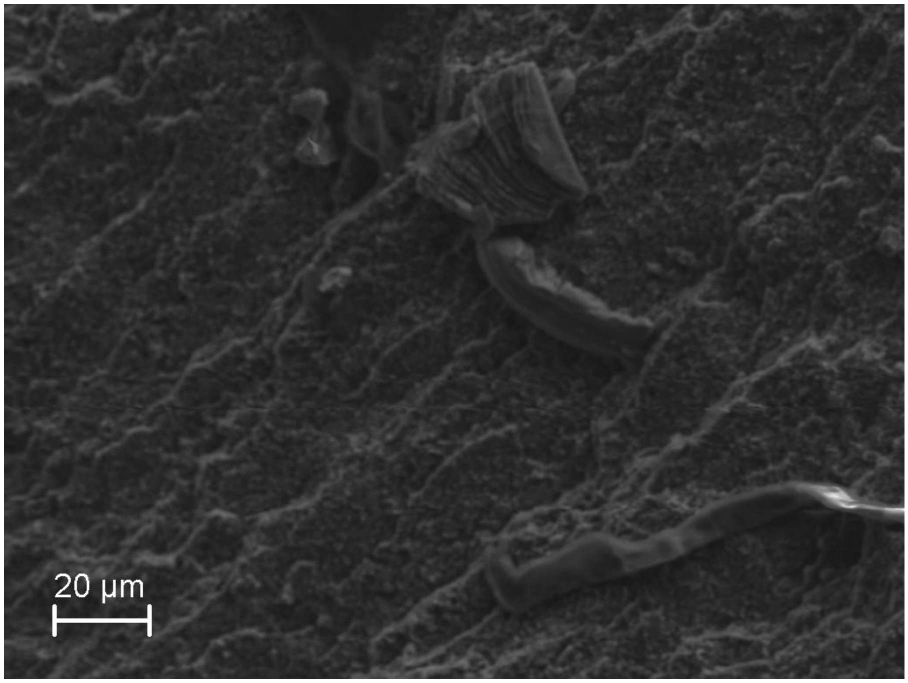

Figure 5: SEM image of SRT-5 fracture surface along Lazy S feature.

EDS analysis was performed on each of these fracture surfaces, to determine whether there was a distinctive composition along the Lazy S, as compared to the weld nugget. The EDS results are shown in Table II. The oxygen content is highlighted, as the Lazy S is shown to have roughly twice as much oxygen present. This is a strong indicator that the Lazy S is in fact formed from the oxides present on the original faying surfaces, which agrees with existing literature related to the Lazy S feature in conventional FSW [5, 6].

Table II: EDS analysis of fracture surfaces.

Element	**SRT-4, Nugget Fracture**		**SRT-5, Lazy S Fracture**	
	Wt%	**At%**	**Wt%**	**At%**
Cu	7.98	2.77	3.78	1.27
O	2.97	4.09	6.77	9.03
C	21.15	38.82	19.46	34.57
Al	63.03	51.50	66.41	52.52
Mg	1.22	1.11	2.18	1.92
Mn	1.56	0.63	0.51	0.20
Fe	1.42	0.56	0.48	0.18
Si	0.67	0.53	0.40	0.31
Total	**100.00**	**100.00**	**100.00**	**100.00**

Conclusions

At the low spindle speed used in this study, the Lazy S feature was observed in all butt weld samples, but was not present in the bead-on-plate weld, confirming that it results from the faying surface of the weld. The Lazy S feature was found to have a distinct impact on the yield strength of SRT welds when presenting in a nearly linear geometry, reducing the strength of the weld to approximately a quarter of the strength of the parent metal. When more distorted geometries were observed, any effects of the Lazy S were superseded by the void defects found on the advancing sides of the welds, and the weld strength was approximately one half that of the parent metal. Further work correlating the geometry of the feature with its impact on weld strength will require the production of welds free of these voids which still clearly exhibit the Lazy S feature.

SEM examination of the different failure modes observed in tensile tests shows that failure in the weld nugget is ductile, while brittle fracture dominates when failure occurs along the Lazy S feature. EDS analysis revealed that the concentration of oxygen along the Lazy S fracture surface is roughly twice that found on a fracture occurring in the weld nugget.

Acknowledgements

The other would like to thank the support of the SDSM&T Advanced Materials Processing and Joining Laboratory (AMP) students and staff. Support for this research was provided by the NSF Research Experiences for Undergraduate Program "Back to the Future" Site Award #0852057.

References

1) H.K. Klages, "The "Lazy S" Feature in Friction Stir Welding of AA2099 Aluminum-Lithium Alloy" (Master's Thesis, Naval Postgraduate School, 2007), 6-7.
2) D.E. Taylor, "Effects of Processing Parameters on the Embrittlement of Self Reacting Friction Stir Welds" (Master's Thesis, Louisiana State University, 2009), 31-34.
3) ASTM Standard E8, 2009, "Standard Test Methods for Tension Testing of Metallic Materials," ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/E0008_E0008M-09 , www.astm.org.
4) M. Warmuzek, Metallographic Techniques for Aluminum and Its Alloys, *Metallography and Microstructures*, Vol 9, *ASM Handbook*, ASM International, 2004, p. 711–751
5) S.R. Ren, Z.Y. Ma, and L.Q. Chen, "Effect of initial butt surface on tensile properties and fracture behavior of friction stir welded Al-Zn-Mg-Cu alloy," *Materials Science and Engineering A*, 479 (2008) 293-299.
6) Y.S. Sato et. al., "Characteristics of the kissing-bond in friction stir welded Al alloy 1050," *Materials Science and Engineering A*, 405 (2005) 333-338.