Description of a Pre-Rotation Defect in Friction Stir Welding of 5456 Aluminum

Kevin J. Colligan

Concurrent Technologies Corporation
15091 Alabama Highway 20, Suite A
Madison, Alabama 35756

Abstract

A new type of welding defect, referred to as a pre-rotation defect, was identified during systematic friction stir welding (FSW) trials in 19-mm 5456-H116 aluminum plate. The defect was attributed to using a tool with an excessive shoulder diameter in relation to the pin diameter. A review of tensile specimens from other projects revealed evidence of this defect in welds in thick aluminum 2519 plate, and mentions of anomalous tensile results found in the literature suggest its possible occurrence elsewhere. This paper presents evidence of the formation of this type of defect and demonstrates its effect on weld strength.

Keywords: Friction Stir Welding, aluminum, pre-rotation defect

INTRODUCTION

Friction stir welding (FSW) has been demonstrated in a wide variety of aluminum alloys, and FSW of 5000-series alloys is generally considered to be routine. Fonda and coworkers at the Naval Research Laboratory [1] evaluated FSW of 12-mm thick 5456 plate and reported high quality welds with nearly uniform hardness and low dislocation density throughout the stir zone (SZ), giving rise to high, uniform ductility in the weld.

The present study demonstrated high quality welds with good strength and ductility in 19-mm thick 5456-H116 plate under a wide range of welding conditions [2]. The goal of this study was to assess the variability of basic mechanical properties of welds with respect to welding conditions. Welds were made using spindle speeds of 264 rev/min and 310 rev/min and travel speeds of 127, 145, 163, 180, and 198 mm/min. The welds were made using a tool with a scrolled, flat shoulder profile and a frustum-shaped pin with threads and flats. The welding tool design parameters are summarized in Table 1. All welds were made in load control with the welding tool axis normal to the workpiece surface. Each weld was cut to produce five transverse tensile test specimens and three transverse macro specimens.

Table 1. Welding Tool Design Parameters

Shoulder Parameters	
Shoulder diameter, mm	35.6
Scroll depth, mm	1.3
Scroll pitch, mm	3.3
Scroll width, mm	1.27
Number of spirals	1
Pin Parameters	
Nominal pin length, mm	18.5
Pin maximum diameter, mm	17.3
Pin minimum diameter, mm	9.7
Thread pitch, threads/mm	18
Number of pin flats	4

PRE-ROTATION DEFECT IDENTIFICATION

In reviewing tensile results from the first iteration of process development welds, the author found that the welds exhibited uncharacteristically high variability in tensile strength, both within individual welds and between replicates of welding conditions. An investigation to identify the root cause of the high strength variability was initiated. Inspection of as-welded materials revealed in a few welded plates a discontinuous crack along the weld crown surface, oriented parallel to the welding direction, as shown in Figure 1. In each case this crack was found biased to the retreating side of the weld crown, where the tool rotation is opposite the tool travel direction. Inspection of macro-etched sections from welds in this test series revealed a microstructural feature that aligned with the surface crack, shown for example in Figure 2.

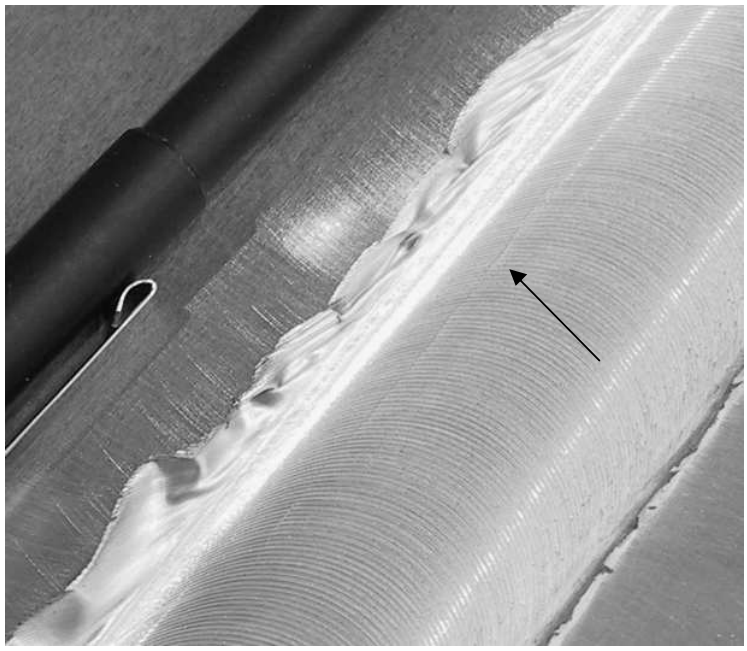

Figure 1. Surface crack observed on some welds.

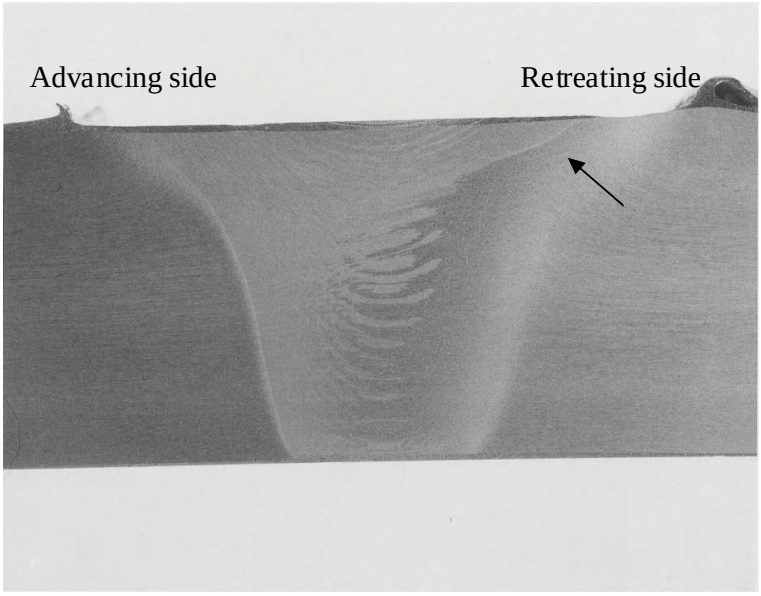

Figure 2. Typical macro-section, noting microstructural feature on retreating side.

Inspection of the fractured tensile specimens that exhibited low strength revealed a curious fracture pattern in many of the specimens. The fractures characteristically originated in the crown surface of the weld along a nearly straight line parallel to the welding direction. As can be seen in Figure 3, below the initial fracture path the fracture typically proceeded along planes of maximum shear stress. A representative tensile specimen was cut and mounted for polishing and etching. The upper portion of the tensile specimen had a fracture profile that matched exactly the microstructural feature noted in the macro sections, shown

in Figure 4. Specimens that exhibited high strength typically failed completely in the heat affected zone (HAZ) of the weld.

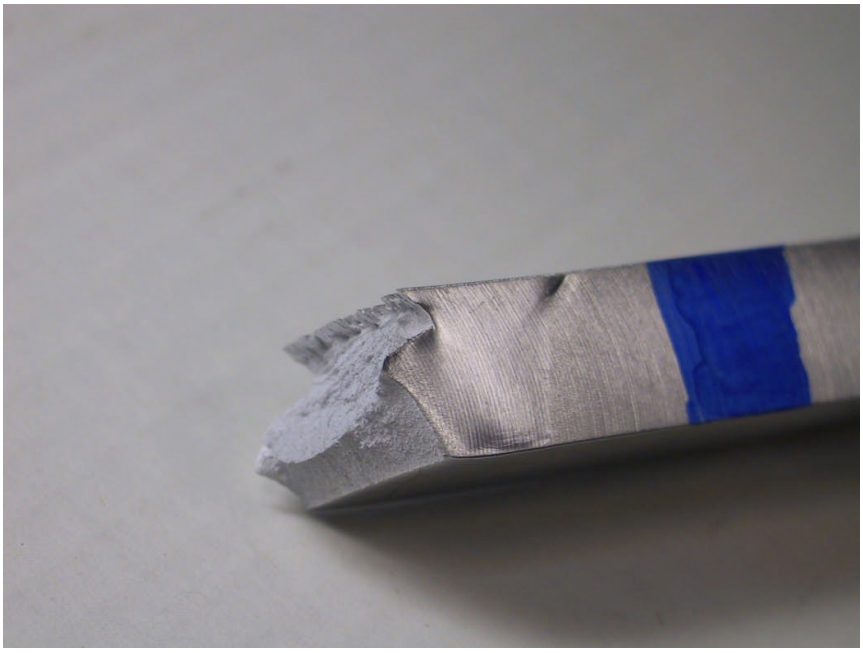

Figure 3. Representative fracture surface, with fracture originating in the weld crown.

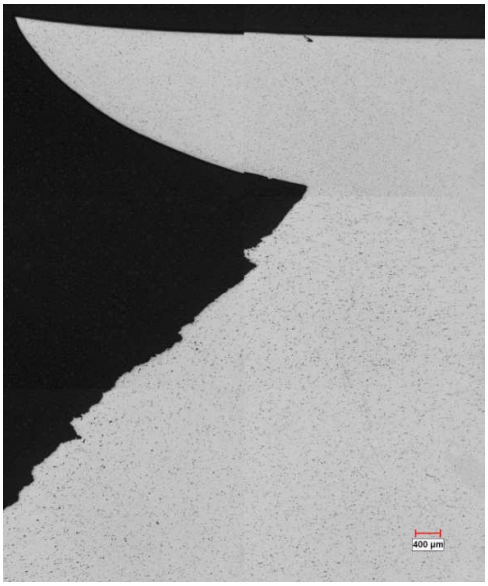

Figure 4. Representative fracture profile in upper portion of the fracture specimen, viewed in the short-transverse plane.

The author speculated that the root cause of these observations was the use of an excessively large welding tool shoulder diameter in relation to the pin diameter, which resulted in premature rotation, or “pre-rotation”, of the joint faying surfaces near the upper surface of the work in advance of the pin under the influence of the shoulder. An experiment

was conducted in which a weld was initiated, and after traveling along the joint for a short distance, the welding tool was stopped by engaging the emergency stop on the welding machine, immediately removing power from the axis drives and the spindle motor, rapidly stopping the tool. The partially welded plate was then cut to produce a specimen with the embedded welding tool pin, the original faying surfaces of the joint, and a short segment of welded material. This specimen was then subjected to serial sectioning, as shown in Figure 5. Slices 1.5-mm thick were taken from the specimen using wire electrical discharge machining (EDM). Each slice was then polished and etched so that the orientation of the original faying surfaces could be inspected at various locations relative to the welding tool.

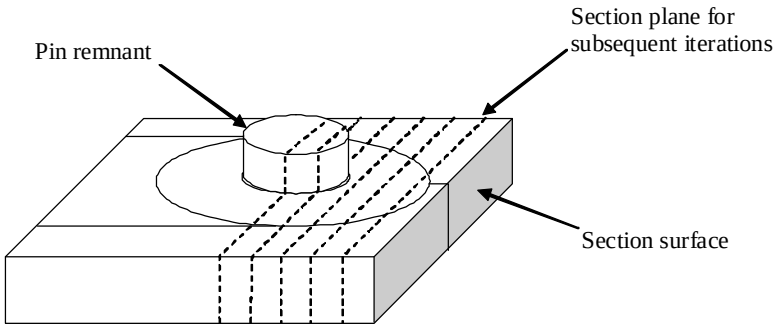

Figure 5. Sketch showing approach for serial sectioning.

A representative section from the serial sectioning experiment, photographed on a light microscope, is shown in Figure 6. The original faying surfaces between the workpieces can be seen as a vertical line in the photograph, the upper portion of which distorted toward the retreating side of the specimen under the influence of the welding tool shoulder. Review of the individual specimens revealed that this lateral distortion of the faying surfaces began at the outer periphery of the welding tool shoulder and continued as the tool progressed, becoming a tight oxide band that rotated to stay just outside of the pin threads, as shown in Figure 7.

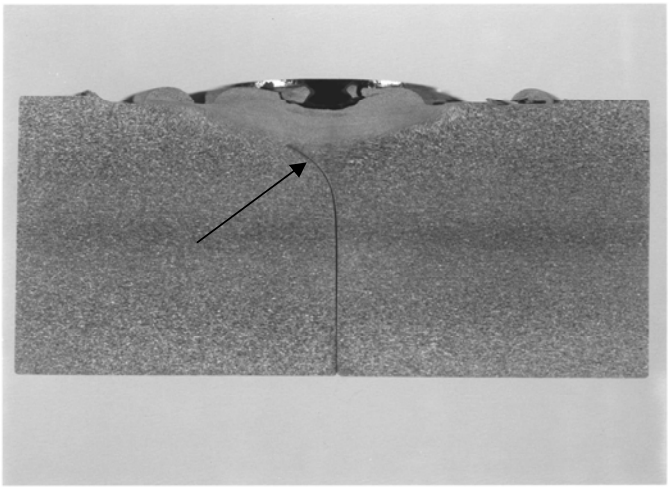

Figure 6. Serial sectioning study, section from slice seven, noting distorted faying surfaces.

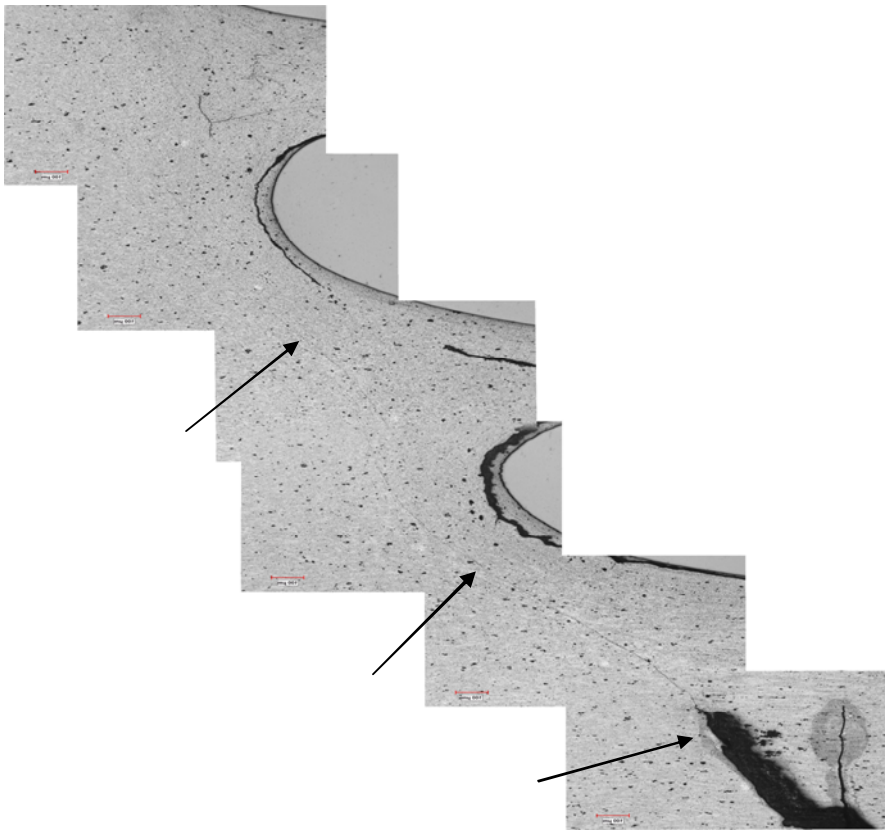

Figure 7. Photomosaic from serial sectioning study, slice nine, noting the tip of the distorted faying surfaces and the compressed remnant oxide layer just outside the pin threads.

A subsequent round of welding process development trials was conducted using a different welding tool design. In these welds, the shoulder diameter was reduced from 35.6

mm to 30.5 mm. All of the other welding tool design parameters remained unchanged. The premise for this change was that by using a smaller shoulder, the distortion of the faying surfaces could be delayed, causing the remnant oxide band to experience higher temperatures as it passed closer to the welding tool pin. Welds were made at the same welding conditions as with the 35.6 mm tool, and five transverse tensile specimens were pulled from each welded plate. The author found that the standard deviation of the five measurements taken for each weld was a good indicator of failure associated with the pre-rotation defect. High standard deviation, defined as a standard deviation greater than 7 MPa based on experience of expected variability in sound friction stir welds, typically indicated that at least one of the specimens failed in this region. Low standard deviation, below 7 MPa, implied that no failures were associated with the pre-rotation defect.

Figure 8 shows the standard deviations of ultimate strength, yield strength, and elongation obtained from the five tensile specimens taken from welds made with the two tools. Two different spindle speeds and five different travel speeds were evaluated for each tool design. As can be seen in the figure, the welds made with the 35.6-mm shoulder diameter tool in Round 1 had many cases where the ultimate strength exhibited high standard deviation. Inspection of the fracture surfaces in these cases of high ultimate strength variability revealed failures associated with the pre-rotation defect. Once the shoulder diameter was reduced to 30.5 mm in Round 2 testing, the standard deviations were lower, especially at the lower spindle speed. These results suggest that there may be some participation of spindle speed in the formation of the pre-rotation defect, leading to higher standard deviations at 310 rev/min in Round 2 than at 264 rev/min. This testing appeared to show that at least a partial solution to the pre-rotation defect depends on reducing the shoulder diameter, with some indication of a spindle speed effect.

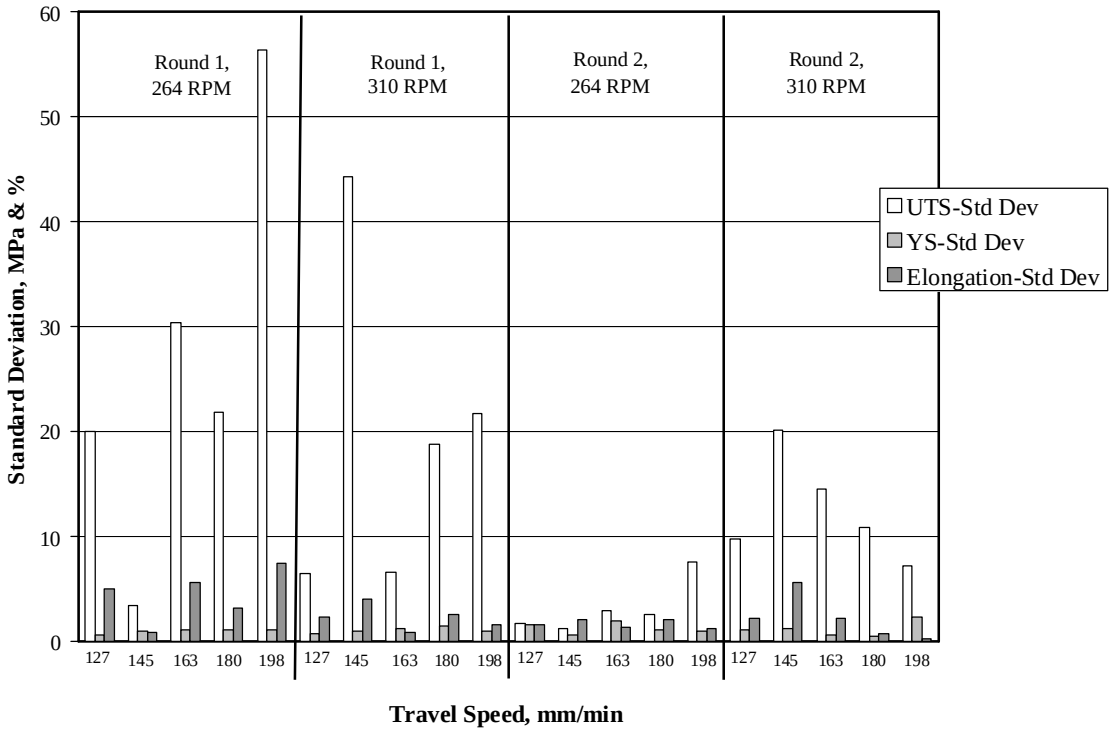

Figure 8. Standard deviation of transverse tensile strength, yield strength, and 50-mm gauge elongation for 35.6-mm shoulder diameter (Round 1) and 30.5-mm shoulder diameter (Round 2), at various travel speeds.

OTHER POSSIBLE CASES OF PRE-ROTATION DEFECTS

The report by Fonda, et al. [1], suggested evidence of an entrained oxide band in welds in 5456 aluminum. In transverse tension tests performed in the 12-mm thick material, one specimen exhibited an anomalous fracture mode, which the authors attributed to an entrained oxide layer. In the same report, a small diameter longitudinal tensile test specimen taken from the upper portion of the weld near the weld centerline exhibited low ultimate strength, which was also attributed to entrained oxides. No mention of a similar defect was found in the literature on friction stir welds in 5083 aluminum, so it is possible that this defect is particularly common in 5456.

Selected tensile specimens from an unpublished study that produced friction stir welds in 25.4-mm 2519-T87 aluminum plate were found to exhibit a similar fracture pattern to that shown in Figure 3. The welding tool used had a smooth, 45.7-mm diameter shoulder, with a frustum shaped pin with threads and flats. The tool was operated in load control with a tilt angle of 2.2°. These welds, made early in the development program in 2000, were made at travel speeds of 20 mm/min and 30.5 mm/min, which is much lower than would currently be considered optimum for this alloy in this thickness. Also, the shoulder diameter would

currently be considered to be unnecessarily large, given the good results obtained later with much smaller tools using a scrolled shoulder. Review of the fractured tensile specimens revealed that some of the specimens fractured in the HAZ, as would be expected for a weld in a heat-treatable aluminum alloy, but some specimens had fractures that initiated in the crown surface of the stir zone, biased toward the advancing side, shown in Figure 9. Note in the right-hand side of the figure that the fracture crosses the weld crown surface in a nearly straight line running parallel to the weld direction. The fracture initiation appeared to coincide with a microstructural feature that was evident in the upper advancing side of the stir zone in a photomicrograph taken from the weld, shown in Figure 10.

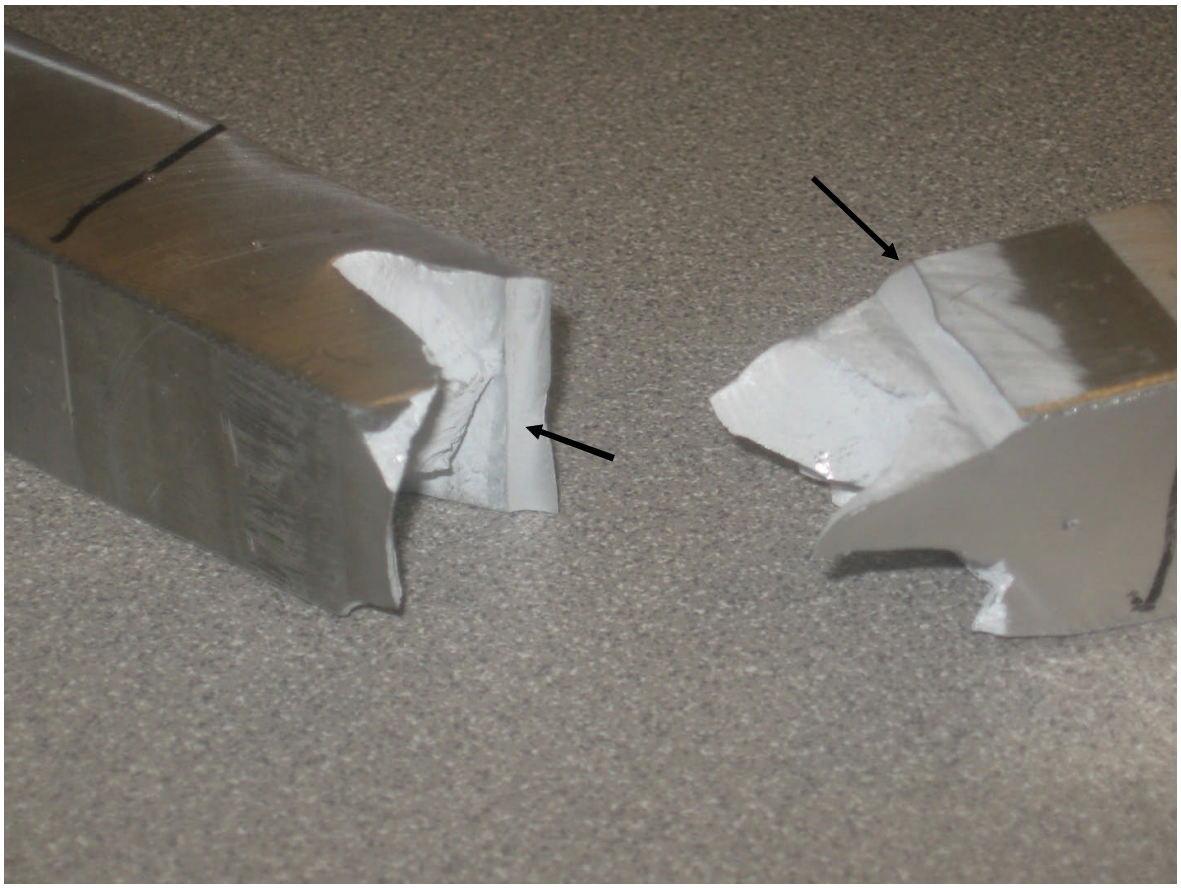

Figure 9. Fractured transverse tensile specimen, 25.4-mm 2519-T87 aluminum FSW, showing fracture initiation site in crown region.

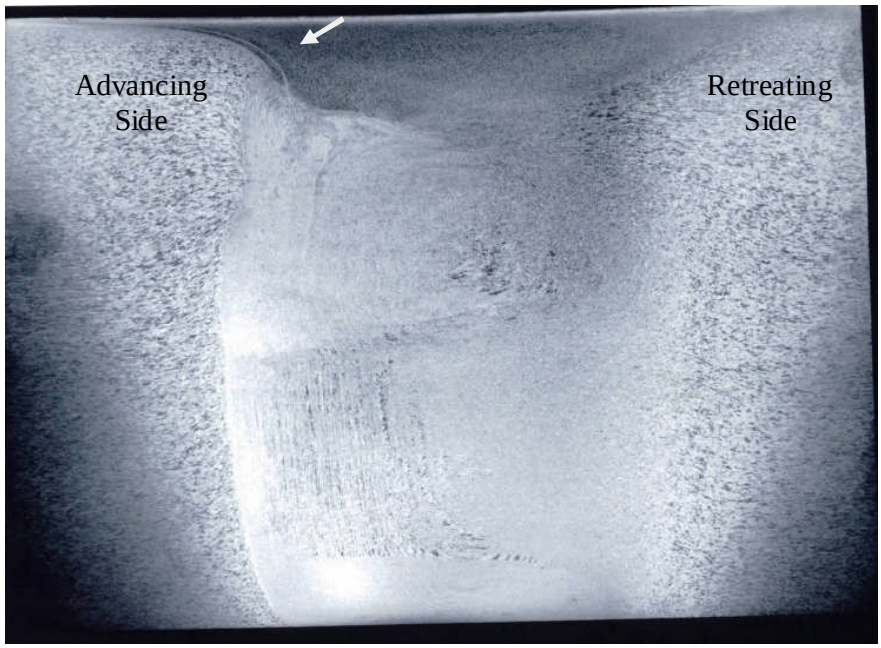

Figure 10. Transverse macro section from FSW in 25.4-mm 2519-T87, showing microstructural feature associated with tensile fractures.

Results from transverse tensile tests in these welds showed high variability compared to welds made later in the test program, after development of procedures using smaller shoulder tools operated at higher travel speeds [3], as can be seen in Figure 11. The latter set of welds was made using a tool with a flat shoulder profile, 30.5-mm in diameter, with spiral shoulder scrolls, at travel speeds of 89 mm/min and 102 mm/min. It was generally found that a larger shoulder diameter produced welds that had inconsistent fracture locations in tension testing, with some specimens failing in the HAZ and others failing with crack initiation in the upper portion of the weld crown, as shown in Figure 9. The specimens with crown-associated fractures typically had lower strength, leading to increased weld strength variability for that weld. In the specimens that were welded with the smaller tool diameter at higher travel speeds, the weld strength variability was typically less than 2 MPa. Although it is not possible now to analyze materials from the earlier welding procedures to isolate pre-rotation of the joint faying surfaces as the root cause of these observations, the tensile data and fracture patterns suggest that this could be the case. In this case it is not clear if the defect formation is solely due to the large shoulder size or to the low travel speed or a combination of these factors, but it seems plausible that the excessively large shoulder diameter plays a leading role in the formation of this defect.

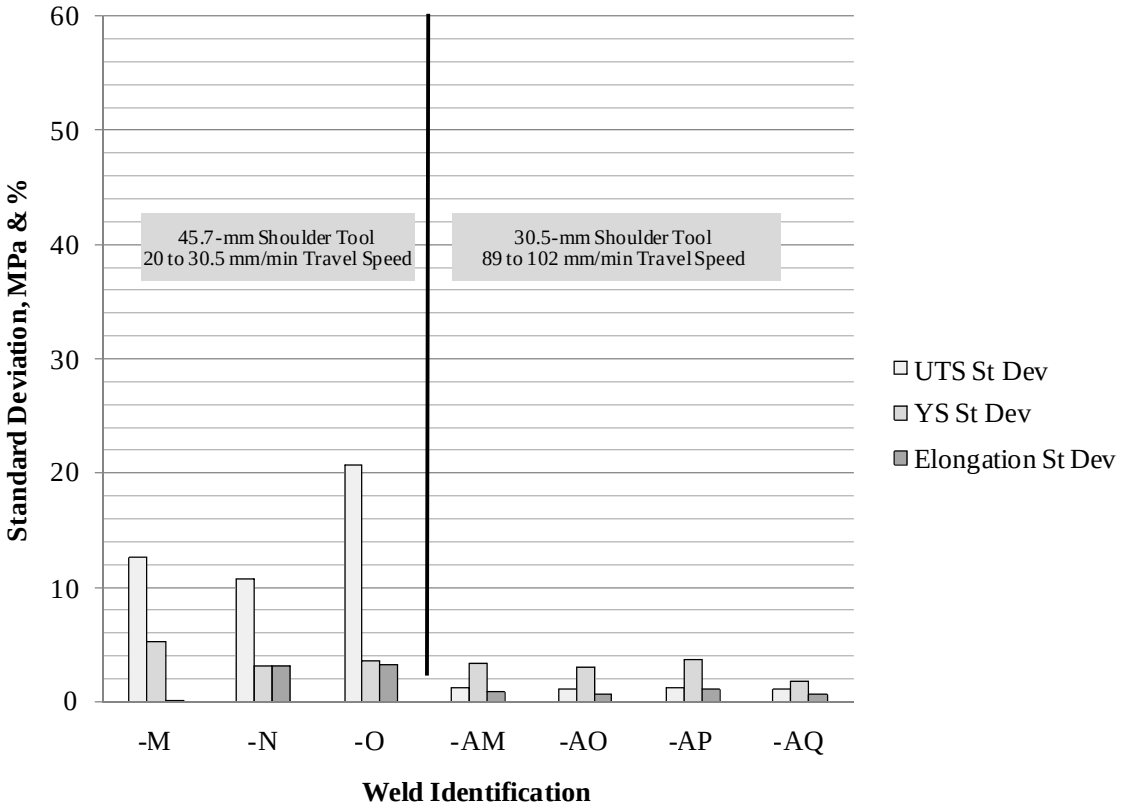

Figure 11. Standard deviation of tensile test results, 45.7-mm shoulder tool and 30.5-mm shoulder tool, 25.4-mm 2519-T87 friction stir welds.

DISCUSSION

It is not uncommon to observe remnants of oxide bands in friction stir welds made in aluminum materials, due in part to the tenacity of the oxide that forms on aluminum alloy surfaces exposed to air, and in part due to the various degrees of mixing that occurs during friction stir welding of different alloys. In most cases, however, these oxide remnants are sufficiently stretched and heated during welding to render them inconsequential in post-weld testing and in routine service conditions. However, it appears that the pre-rotation defect noted in this study can be sufficient to degrade the properties of the joint to the point of being detectable by transverse tensile testing and face bend testing. This has implications for many service conditions, and may be especially problematic for post-weld forming operations that impart plastic strain specifically in the crown region of the weld.

CONCLUSIONS

In this study, a new type of FSW defect was identified and traced to a possible root cause. The pre-rotation defect consists of a tight, oxide-rich remnant of the original faying

surfaces in the upper portion of the weld, which is sufficiently continuous to locally reduce strength or ductility in testing or service. As the name implies, it is thought to originate from early rotation of the upper portion of the joint out of the path of the pin, under the influence of shear flow produced by the shoulder in advance of the pin, causing the original faying surfaces to remain sufficiently intact to affect local properties. Evidence of this defect was studied primarily in 19-mm 5456-H116 aluminum plate, but similar characteristics were also identified in 25.4-mm 2519-T87 aluminum welds, implying that this may not be solely associated with 5456 materials. The presence of this defect type may be particularly problematic in applications where post-weld forming processes impose high levels of plastic strain in the weld crown.

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