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Abstract

Friction stir welding (FSW) is rapidly penetrating the welding market in many materials and applications, particularly in aluminum alloys for transportation applications. As this expansion outside the research laboratory continues, fitness for service issues will arise, and process control and NDE methods will become important determinants of continued growth. The present paper describes research into FSW weld nugget flaw detection within aluminum alloy lap welds. We present results for two types of FSW tool designs: a smooth pin tool and a threaded pin tool. We show that under certain process parameters (as monitored during welding with a rotating dynamometer that measures x, y, z, and torque forces) and tooling designs, FSW lap welds allow significant non-bonded interface lifting of the lap joint, while forming a metallurgical bond only within the pin region of the weld nugget. These lifted joints are often held very tightly together even though unbonded, and might be expected to pass cursory NDE while representing a substantial compromise in joint mechanical properties. The phenomenon is investigated here via radiographic and ultrasonic NDE techniques, with a copper foil marking insert (as described elsewhere) and by the tensile testing of joints. As one would expect, these results show that tool design and process parameters significantly affect plactic flow and this lifted interface. NDE and mechanical strength ramifications of this defect are discussed.

Introduction

This paper discusses the formation of interface lifting flaws, see Figure 1, and the difficulty of identifying these flaws using standard non-destructive evaluation (NDE) methods. "Interface lifting" in the context of the heavy pastic deformation involved in FSW refers to the movement, as a unit, of the prior interface of a lap weld, identified in other work as a critical sheet interface. [1] Although the surrounding material may be heavily worked, the interface itself is not stirred by the tool sufficiently to break up the surface oxides typical of aluminum and allow true solid state welding to occur.

This phenomenon can be quite subtle in its engineering consequences, because the bonding, while dinstinctly failing in an atomic sense, is nonetheless quite tight in a mechanical sense. These interfaces appear to pass ultrasonic waves quite efficiently, so that conventional ultrasonic tesing (UT) indicates a sound bond. Under destructive examination, metallography reveals a solid-looking interface in the as-ground or as-polished state, even maintaining this appearance after a degree of etching typical of microstructural examination, *e.g.,* 1-2 minutes under hydrofluoric acid. Many welds have undoubtedly been made that met these test criteria and were passed as sound.

Under more severe testing, however, approximating destructive service conditions, the weakness of the interface becomes more apparent. What would normally be considered severe over-etching in a metallographic context (*e.g.,* 10 minutes under 3N NaOH) deeply trenches the lifted interface. More significantly, stress rupture tensile testing causes the structure to part at the interface, indicating that such a failure could also occur in service. Fatigue testing was not performed in this investigation, but there is the potential for that type of failure, as well. [2]

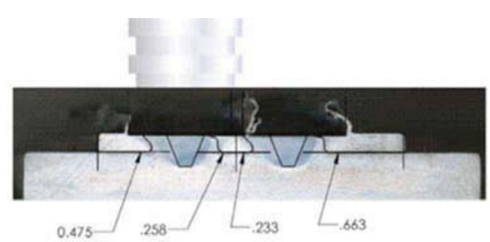

Figure 1: FSW tool superimposed over a lap welded plate exhibiting interface lifting at the edges of two welds

The present work describes a test matrix of Friction Stir lap welds, and the subsequent identification, and difficulty of identification, of the lifted interface phenomenon via UT, metallography, and tensile testing.

Experimental

Materials

All FSW were performed on 6061-T6 aluminum. Coupon dimensions were nominally 101.6 mm x 203.2 mm x 3.175 mm (4 in. x 8 in x 0.125 in.) and 101.6 mm x 203.2 mm x 9.525 mm (4 in. x 8 in x 0.375 in.). Lapped material (3.175 mm over 9.525 mm) was clamped with hold-downs at two points along both long sides to a copper, water-cooled plate, 609.6 mm x 127 mm (24 in. x 5 in.), sitting on a steel fixture approximately 50 mm (2 in.) thick if water cooling was used. Otherwise a steel plate (6.35 mm or 0.25 in.) was placed between the copper cooling plate and the FSW coupons. Typically three runs were made on each set of plates.

Tools

Four different tool designs, all made of T15 tool steel, were used in the conduct of our experiments and they differed in pin and shoulder configuration. The first tool was plain, i.e., it had no scrolls cut into it. The second tool was constructed with a scrolled shoulder and a plain pin, while the third tool was made with a plain shoulder and a scrolled pin. The fourth tool had a scroll on both the shoulder and the pin, see Figure 2.

Figure 2: All tools were based on this scrolled pin and shoulder design. The tool with no scrolls was flat on the shoulder and the pin was smooth. The shoulder of the scrolled pin tool was also flat. The unscrolled pins were the dimensions of the pin above prior to cutting the scroll into it.

FSW Procedures

All FSW were conducted using a 152.4 mm/min (6 in/min) travel speed and a 177.8 mm (7 in.) travel length. Spindle speed was divided into two parts: plunging rotational speed and traveling rotational speed. Typically a run was conducted using a plunging spindle velocity of 1800 rpm and then the spindle speed would be dropped to the chosen velocity for use during travel. The exception was when the spindle speed for travel was 2000 rpm and then the plunging spindle speed was increased to 2000 rpm. Plunging rate was always 0.01 ips (0.6 ipm) and typically to a depth of 5.715 mm (0.225 in.). Depth could be adjusted either up or down in 0.127 mm (0.005 in.) increments prior to initiation of or during travel as deemed necessary. Parameters for the first set of welds (welds 1 through 18) are described in Table 1. Typically three to four welds are run on each plate with welds generally 0.8 in. to 1.1 in. apart on the centerline.

Table 1: Plunge and travel spindle speeds used for the various FSW runs along with tool type and whether water cooling was used. The "scroll on tool" column indicates where the scroll was located; "Both" indicates there was a scroll on the pin and on the shoulder.

Weld #	Plunge Spindle Speed	Travel Spindle Speed	Scroll On Tool	Water Cooled Table
1	1800	1000	None	Yes
2	1800	1400	None	Yes
3	1800	1800	None	Yes
4	1800	1000	Pin	Yes
5	1800	1400	Pin	Yes
6	1800	1800	Pin	Yes
7	1800	1000	Shoulder	Yes
8	1800	1400	Shoulder	Yes
9	1800	1800	Shoulder	Yes
10	1800	1000	Both	Yes
11	1800	1400	Both	Yes
12	1800	1800	Both	Yes
13	1800	1200	Both	Yes
14	1800	1600	Both	Yes
15	2000	2000	Both	Yes
16	1800	1200	Both	Yes
17	1800	1600	Both	Yes
18	2000	2000	Both	Yes
19	1800	1200	Both	No
20	1800	1600	Both	No
21	2000	2000	Both	No
22	1800	1000	Shoulder	No
23	1800	1400	Shoulder	No
24	1800	1800	Shoulder	No
25	1800	1000	Pin	No
26	1800	1400	Pin	No
27	1800	1800	Pin	No
28	1800	1200	Both	Yes
29	1800	1600	Both	Yes
30	2000	2000	Both	Yes
31	2400	2400	Both	Yes

Experiments were performed with and without water cooling. When cooling was used the inlet water temperature into the copper-cooling plate was between 44°F and 48°F while the outlet temperature was between 46°F and 48°F. Temperatures at the inlet and outlet were measured with inline thermocouples (Omega HH12A).

A second set of experiments were performed and are described as Welds 19 through 31 in Table 1. After welding, the top surface of the top plate was machined to just below the top of the weld surface in order to remove weld indications (the exit hole remained) and flash. This was done in order to provide a "blind" specimen for ultrasonic inspection as described in the next section.

It should be noted that the present work involves relatively high spindle speeds, and high spindle velocity to travel speed ratios, compared with other work in the literature. [1,3,4] This is because the orientation of the present project has been towards the application of FSW to robotic welding and the processing of complex shapes, where it is desirable to maintain low forces on tool and workpiece. Depending on tool design and weld geometry (both important factors), these other workers have found optimal welding parameters at lower speeds.

Ultrasonic Testing

Two ultrasonic testing methods were conducted on each plate. Both methods of testing were run blind.

In the first method, the plates were ultrasonically inspected using a 40 MHz transducer in pulse/echo (PE) mode from the top. The transducer has a 0.006 to 0.008 in. beam size with and extended depth of field. It is capable of characterizing aluminum structures as small as 0.005 in. by 0.005 in. (depth and diameter). The ultrasonic inspections were obtained using a 1 GHz sampling rate with 150 µm resolution. The data collection gates were set to ensure that the bond area between the two plates was included. Data collection gates were configured to show 0.001 in. slices within the aluminum. An additional single composite gate showing all structural changes within the same region was also used, see Figure 3. Data acquisition was performed on a Sonix WinIC Ultrasonic Inspection System.

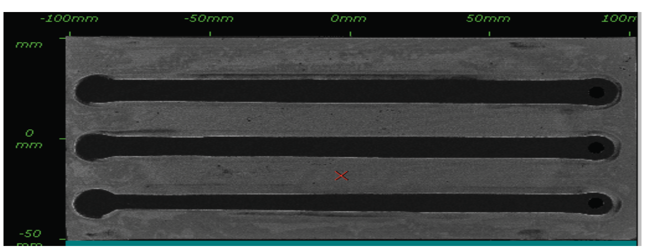

Figure 3: An example of compiled data from PE ultrasonic scans of a set of FSW plates from the top using a 40MHz transducer with an extended depth of field. The wide, dark stripes in the grey rectangle are the ultrasound pulses passing through the FSW areas and not returning to the transducer. The grey areas are the pulses returning to the transducer from the bottom of the thinner top plate. Contrast of image was reduced in Word to improve print quality.

The second ultrasonic method used an OlympusNDT 64L5-A2 phased array transducer (5 MHz, 64 element linear array, 0.59 mm center to center pitch between elements, passive aperture of 10 mm) attached to an OlympusNDT SA2-N45S rexolite wedge (nominal angle to produce 45° transverse or shear waves into steel). The transducer was driven by a 32/128 FocusLT also produced by OlympusNDT. Acquisition and analysis software used was Tomoview 2.7 R3.

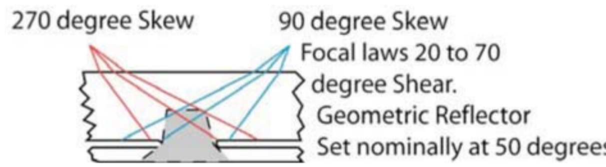

Figure 4: Sketch of ultrasonic sweep for UT array scans of the FSW plates. Transducer scanned from the bottom of the plate on either side of the weld traveling in the direction of the weld.

With no particular information about the expected location of weld features that might be present, a generic sector scan (varying the angle of incidence of a set of focal laws from 20° to 70° for transverse mode sound waves) was performed. The sound speed for transverse waves in aluminum used for focal law generation and image construction was that given in Tomoview focal law calculator (3130 m/s). Thirty-two of the elements were used for the active aperture. The focal laws were set to have optimal focus at 10 mm deep which is the approximate depth of the interface between the plates. Scans with the wedge rotated to a skew of 90° and 270° to the weld were performed to examine the weld from both sides, see Figure 4. It was noted in preliminary scans that a consistent geometric reflector was created by the welding process at the 1/8 inch to 3/8 inch plate interface. The geometric reflector was used as a datum/reference point and set to occur on approximately the 50° incident focal law for each scan, see Figure 5.

Scans were completed with linear slides with quadrature optical encoders to give the instrument position data. The focal laws were triggered every 0.5mm (i.e. all of the sound paths were generated and acquired every 0.5mm of travel).

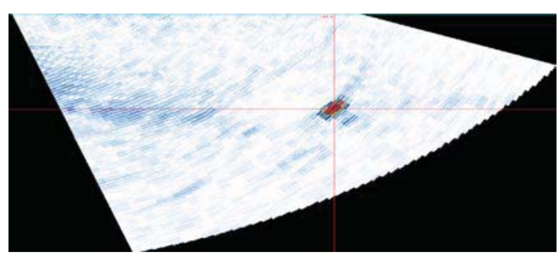

Figure 5: Sector scan of the focal laws showing the nominal geometry feature of the penetration of the weld at the interface between the plates.

Tensile Testing
After the plates had been inspected ultrasonically, tensile testing was performed to determine if the weak zone boundary caused by lifting would also serve to initiate fracture of the upper plate. Specimens approximately 1 inch wide, transverse to the welding direction, were removed. Because of the closely spaced multiple welds on each coupon, grips overlapped the outer welds, only the middle weld was tested, and the tensile testing grips overlapped the other welds on each coupon. Testing was performed on a standard load frame at a crosshead speed of 4 mm/min.

Fracture stresses in the lap welded plate were not determined because the bulk of the load was transmitted through the thicker, mostly unaffected base metal. This stress could be determined relatively easily with a slightly different specimen design, however.

Results and Discussion

Initial Experiments
Cross-sections of welds were treated with 3N NaOH for time periods varying from 10 minutes to 3 hours in the first set of experiments, see Figure 6. In some instances the lifting defect would not be visible after the short exposure to NaOH but would become visible during longer exposure.

Cross-sections of the no-scroll tool welds (welds 1 – 3) indicate that although the interface between plates was not lifted at the spindle speeds used, plastic deformation was inadequate to totally consume the interface. This tool also produced a consistent wormhole in the lower portion of the weld. Mixing did improve as the spindle speed increased.

The shoulder scroll tool (welds 7 – 9) produced a better weld, particularly at a higher spindle speed. The wormhole also decreased in size as spindle speed increased. There was no indication of a lifted interface with this tool but the interface within the weld was not always entirely consumed.

Lifting of the interface between the two plates became evident in the welds made with the pin scroll tool (welds 4 – 6). Notice the right-hand edge of the weld in figure 6 below. Even in a 10 minute NaOH etch the curled back interface is evident. This tool did not stir so well that the interface on the left-hand side of the weld was entirely consumed either.

Friction stir processing with the pin and shoulder scroll tool (welds 10 – 18) produced the most prominent lifting of the interface. The left hand interface is pulled through the center of the weld. As spindle speed increases, it is lifted to the surface of the top plate. The right hand interface is lifted and folded back toward the right to the surface of the plate. The right hand lifting is generally consistent between spindle speeds when seen.

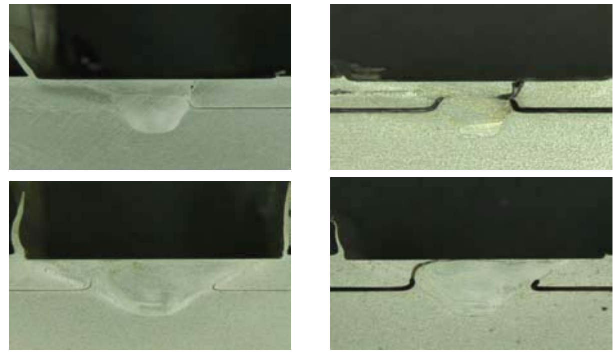

Figure 6: Top from left: 10- and 170-minute etches of cross-sections from 1800 rpm pin scroll tool FSP. Bottom from left: 20- and 170-minute etch of cross-sections from 2000 rpm pin and shoulder scroll tool FSP. The lifted interface is evident even in the photographs from shorter etch times.

Ultrasonic Inspection Experiments
After the plates were machined and ultrasonically tested, they were sectioned and a 3N NaOH etch was used for various lengths of time to bring out the interface between the processed plates.

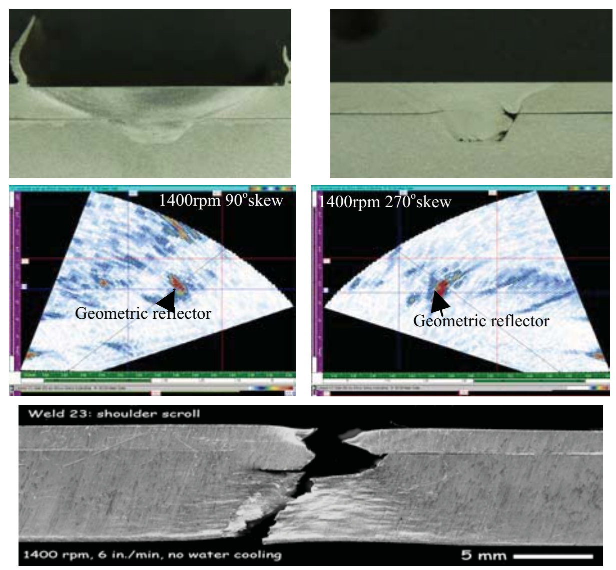

Figure 7: Top left: 30-minute etch of a cross-section from the 1400 rpm Shoulder Scroll tool FSP with cooling. Top right: 20-minute etch of a cross-secton from the 1400 rpm Shoulder Scroll tool without cooling. Center: Phased Array UT of the 1400 rpm Shoulder Scroll tool without coolin,g noting the Geometric Reflector. Indications of flaws were seen in the bottom plate in numerous other locations. Note that the scans have been oriented so that they are looking up through the bottom of the plate. Bottom: Tensile test of the 1400 rpm Shoulder Scroll tool FSP. The nugget remains in the left-hand portion of the specimen.

The shoulder scroll tool used without cooling during processing produced more severely flawed welds as compared with those made with cooling, as can be seen in Figure 7. The immersion UT and the phased array UT (PAUT) detected the wormholes in all three welds made under these conditions. Tensile testing showed failure with more plastic deformation through the nugget for the 1400 rpm process (center location of the plate).

The pin scroll tool used without cooling during processing produced a weld comparable to that made with cooling, see Figure 8. The interface is not destroyed in either weld. The right-hand portion is lifted to the surface of the plate and the left-hand portion continues through the processing although at a lesser depth than the original interface level. The immersion UT did not note the lifted interfaces though it did identify surface tearing and other superficial defects. The PAUT noted some flaws and possibly a lifted interface at various points along the weld. Tensile testing showed failure at the lifted interface for the 1400 rpm process. Note the well defined, intact interface in the left-hand portion of the tensile specimen in Figure 8 below.

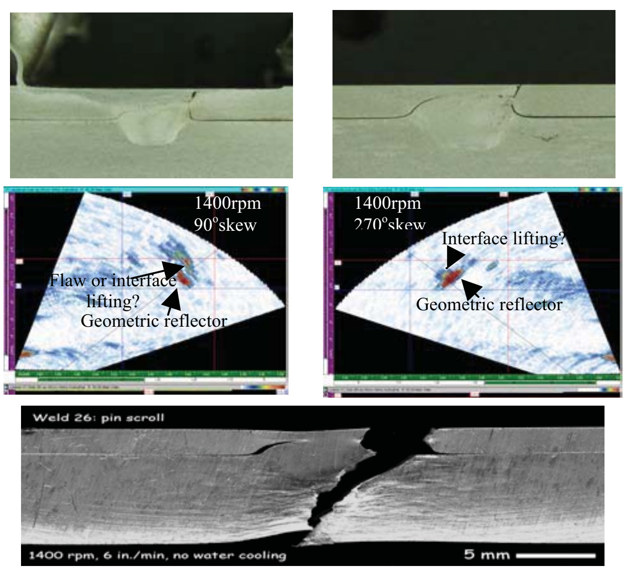

Figure 8: Top left: 20-minute etch of a cross-section from the 1400 rpm Pin Scroll tool FSP with cooling. Top right: 20-minute etch of a cross-secton from the 1400 rpm Pin Scroll tool without cooling. Center: PAUT of the 1400 rpm Pin Scroll tool without cooling noting the Geometric Reflector and possible lifted interface. Bottom: Tensile test of the 1400 rpm Pin Scroll tool FSP. Failure occurred at the lifted interface.

The pin and shoulder scroll tool used without cooling provided a product with fewer defects. Immersion UT did not indicate lifting but did show areas just outside the process bounds where UT waves were able to penetrate as shown in Figure 9 below. PAUT of the 1600 rpm pin and shoulder tool trial clearly showed the geometric reflector at 50° and possibly the lifted interface on each side of the process, see Figure 10. A standard 10% Hydrofluoric acid etch for 1 to 2 minutes begins to highlight the lifted interface while a 60 minute etch using 3N NaOH clearly shows the interfaces. Tensile testing shows failure at the lifted interface but this time on the left-hand side of the process.

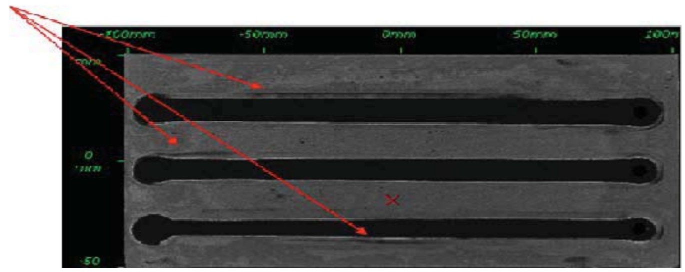

Figure 9: Immersion UT of Pin and Shoulder Scroll tool processing on plate without water cooling. Red arrows indicate locations where the "fit" between the plates is so tight that the UT waves pass through. From the top, processes are 2000 rpm, 1600 rpm, and 1200 rpm.

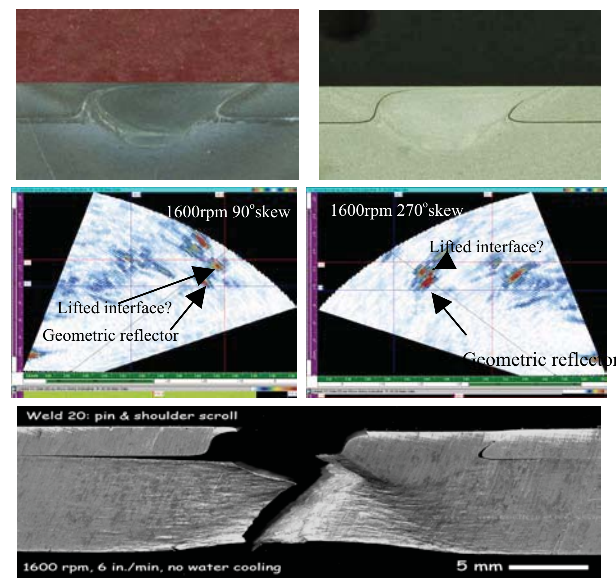

Figure 10: Top left: 1- to 2-minute HF etch of a cross-section from the 1600 rpm Pin and Shoulder Scroll tool FSP without cooling. Top right: 60 minute NaOH etch of a cross-secton from the 1600 rpm Pin and Shoulder Scroll tool without cooling. Center: PAUT of the 1600 rpm Pin and Shoulder Scroll tool FSP without cooling noting the Geometric Reflector and possible lifted interface. Bottom: Tensile test of the 1600 rpm Pin and Shoulder Scroll tool FSP. Failure occurred at the left-hand lifted interface.

PAUT examination of the 2000 rpm pin and shoulder tool specimen without cooling during processing did not indicate lifting of the left-hand surface (and possibly the right-hand surface in places) although the cross-sections clearly showed both, see Figure 11. Tensile testing was not performed as this trial as there was not enough material for the instrument to grasp.

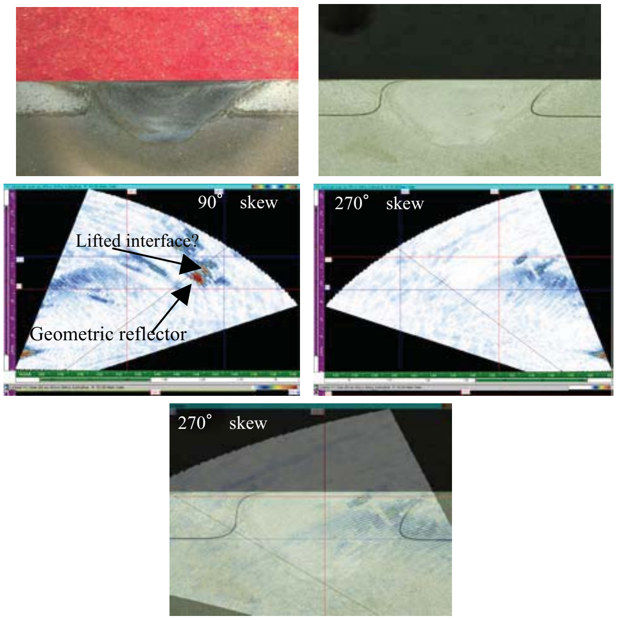

Figure 11: Top left: 1- to 2-minute HF etch of a cross-section from the 2000 rpm Pin and Shoulder Scroll tool FSP without cooling. Top right: 60 minute NaOH etch of a cross-secton from the 2000 rpm Pin and Shoulder Scroll tool without cooling. Center left to right: 90 and 270-degree skew PAUTs of the 2000 rpm specimen at the location of cross-sections shown at top right. Note the Geometric Reflector and possible lifted interface in the 90-degree skew and the absence in the 270-degree skew. Bottom: 60 minute NaOH etched cross-secton (from top right) overlaid with the 270-degree skew phase array UT (center right).

When water cooling was used during processing with the pin and shoulder scroll tool, "trenches" formed along the top surface of the plate as well as just below it in the four trials run. All four of the trials were on one set of plates. The immersion UT picked the "trench" defects up but did not call out any lifting of the interface. The phase array UT data showed probable evidence of interface lifting in the 90-degree skew but not in the 270-degree skew. Tensile testing of the 2000 rpm weld showed failure at lifted interface of adjacent weld (2400 rpm) and at the nugget boundary of the 2000 rpm weld, see Figure 12.

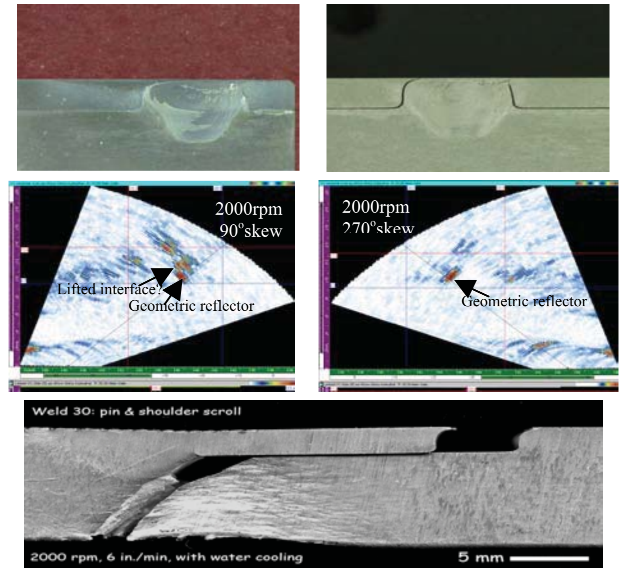

Figure 12: Top left: 1- to 2-minute HF etch of a cross-section from the 2000 rpm Pin and Shoulder Scroll tool FSP with cooling. Top right: 20-minute NaOH etch of a cross-secton from the 2000 rpm Pin and Shoulder Scroll tool with cooling. Center left to right: 90- and 270-degree skew PAUTs of the 2000 rpm specimen at the location near the cross-sections shown at top right. Note the Geometric Reflector and possible lifted interface in the 90-degree skew. Bottom: Tensile test of the 2000 rpm Pin and Shoulder Scroll tool FSP. Failure occurred at the adjacent weld's (2400 rpm) left-hand lifted interface and at the 2000 rpm nugget.

Conclusions

Under some welding conditions, interface lifting into the weld zone can occur, which serves as a failure initiation site under load, and could weaken a FSW joint in service.

This phenomenon is difficult to detect with conventional NDE methods, and even requires enhanced techniques with normal destructive techniques such as metallography. FSW is a relatively new process that is entering service in a number of critical areas, and the possibility of such defects should be borne in mind.

This problem is exacerbated by welds performed at high spindle speeds and low travel speeds (high advance to spindle speed ratio), a regime of interest for robotic FSW because of the reduced forces involved, but may be reduced at lower ratios.

Acknowledgments

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