

Refill Friction Stir Spot Welding Development

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Abstract

High-strength aluminum alloys are of increasing interest to the aerospace and automotive industry for critical high-strength components. B-pillars and door beams being of particular interest to the automotive industry Refill friction stir spot welding (RFSSW) offers an attractive means of joining these difficult-to-weld alloys since bulk melting is avoided and no exit hole is left. In this study, an aluminum-copper-lithium alloy and AA7075-T6 were refill friction stir spot welded. The effects of welding parameters on mechanical properties and fracture behavior were examined. Lap shear and cross-tension testing were performed to determine effect of parameters on mechanical strengths. Metallography was used to examine weld morphology. Cross tension and lap shear strengths on the order of 0.6 and 6.7 kN, respectively, were obtained in the Al-Cu-Li material. Cross tension and lap shear strengths on the order of 2.1 and 6.4 kN, respectively, were obtained in 7075-T6. While the Al-Li-Cu material in the T3 temper is lower in cross tension, it is expected that the T8 temper of the Al-Cu-Li material would exhibit similar performance as the AA7075-T6 material. Mixed mode failures including button pull and interface failures were noted across both alloys at identical parameter sets. Fracture surfaces of failure types were characterized via scanning electron microscope.

Introduction

Friction stir spot welding (FSSW) is a solid-state joining technology capable of single point attachment in sheet metals. This technology is a variant of friction stir welding (FSW). Whereas FSW creates a linear joint, FSSW makes a spot weld similar to a resistance process. There are three variants of FSSW most often discussed in open literature and covered by ISO standards: traditional, swept, and refill.⁽¹⁾ The traditional method is very similar to the plunge sequence of a friction stir weld. A single-piece, non-consumable tool is plunged into the material, held for a period of time, and then retracted leaving an exit hole. The swept variant utilizes the same plunge sequence, while incorporating translation along a circular path.

RFSSW uses a three-part tool consisting of a rotating pin and shoulder, and a clamping ring. The standard sequence of RFSSW consists of four parts. First, all three components clamp down on the part to be welded. Second, the shoulder plunges into the part while the pin retracts, capturing the material displaced by the shoulder. Third, the shoulder retracts while the pin plunges, depositing the displaced material back into the weld. Finally, the tool set unclamps from the part. A cross section of the tool set, as well as the standard plunge sequence, is shown in Figure 1.

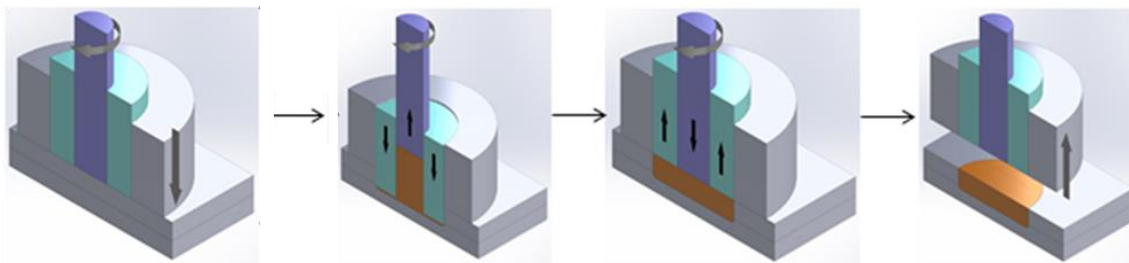


Figure 1. RFSSW Shoulder Plunge Sequence

The main advantages of RFSSW over traditional FSSW are the elimination of the keyhole, and minimization of material loss during welding. Elimination of the weld keyhole decreases the susceptibility of the bond area to corrosion. No pockets exist that would otherwise hold debris or other foreign contaminants. Refill welds have better tensile strengths than those made using the traditional variant. However, these welds do not perform as well in fatigue.⁽²⁾

Research has been conducted on the FSSW of AA7075-T6 using the traditional and refill variants.^(2, 3, 4) The biggest challenge is evidence of melted films.^(2,4) This is related to the formation of an aluminum-zinc eutectic that can form at typical forging temperatures for this process. However, joint strengths on the order of 7 kN and 12.4 kN have been achieved in 2-mm thick sheets welded using the refill and traditional variants, respectively.^(2, 3) Little work has been done on the FSSW of aluminum lithium alloys. However, research using FSW for the joining of aluminum lithium alloys indicates that, similar to AA7075, excessive heat input leads to lower joint strengths, joint softening, and liquation.⁽⁵⁻⁸⁾

The aluminum alloys used in this study were chosen for their high strength and interest to general industry. AA7075-T6 is a well-known alloy in industry, with ultimate strengths on the order of 574 MPa. The aluminum-copper-lithium alloy used is a developmental material that is being considered as a replacement for AA2195. It is an aluminum-copper-lithium alloy, giving it an ultra-high strength-to-weight ratio. The product was used in the forming T3 temper to facilitate part mechanical fabrication instead of the final T8 temper typically associated with this product. This project focused on developing welding parameters for the chosen materials. Additionally, the mechanical performances of welded joints were examined and used to determine the weld parameter effects on tensile strengths. Finally, the fracture surfaces of the welded joints were examined to determine failure mode at the bondline.

Experimental Procedure

Refill Friction Stir Spot Welding Machine

Welding trials were conducted using a Harms & Wende RPS100 refill friction stir spot welding system. This machine has a maximum plunge distance of 10 mm, spindle speeds up to 3,300 RPM, and maximum pin and shoulder axial speeds of 5.7 mm/s. Additional machine capabilities include a 2.2 kW spindle drive, 21 N-m spindle torque, and 11 kN force capacity. The RPS100 has the option of being mounted to a robot or a stationary stand. The unit is shown in Figure 2(a), with details of the tooling provided in Figure 2(b). The tooling set used throughout the experimental trials was purchased from the manufacturer and was model WZ18. The WZ18 toolset had a 9-mm diameter rotating shoulder and 6-mm diameter rotating pin.

Weld schedules consist of multiple line commands that are executed sequentially. An example of the weld schedule interface is shown in Figure 3. Plunge values are input by the user, and retract values are automatically generated by the machine based upon volume displacement. Weld cycle times listed in this study are the sum of times to complete each line of the weld schedule.

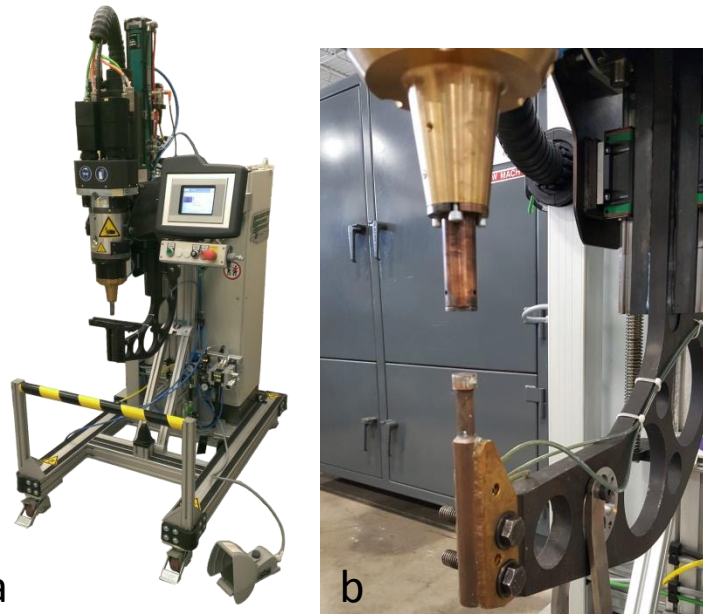


Figure 2. Harms and Wende RPS100

RPS100 Parameter						
2. Welding parameters						
PKT	Time [sec]	Spindle n[1/min]	Sleeve Travel[mm]	Pin	Sp Interpol.	H
DR	0.000	300	- 0.500	- 0.500	2	80
1	0.200	1800	0.000	0.000	2	4
2	1.000	1800	1.340	- 1.310	2	4
3	1.000	1800	0.000	0.000	2	80
4	0.200	1800	- 0.205	0.200	2	80

Figure 3. Weld Schedule Program on Machine

Tooling

Two anvils were used to make weld specimens – one for lap shear and another for cross tension. The anvil used for lap shear specimens was fixed and directly water cooled. It featured secondary tooling around the anvil, which located material coupons for welding. Due to tooling interferences with the lap shear anvil, a second version was needed to create the cross tension specimens. This anvil included a self-aligning swivel foot feature to account for angular misalignment caused by machine deflection and was indirectly water cooled. Cross-tension specimens were made with a hand-held template that aligned the coupons and located the assembly relative to the welding anvil.

Toolset Cleaning

In order to maintain consistent weld quality, it was necessary to periodically clean the toolset in order to minimize material build up during trials. Two methods for keeping the toolset clean were used. First, in between welds, a cleaning cycle function of the machine was used. This is an option that was manually selected and run as needed from the machine user interface. The

cleaning cycle runs the toolset through a weld cycle while leaving the head in the unclamped position. Second, after many welds, cleaning cycles were insufficient to remove deeply ingressed aluminum. For a thorough cleaning or when alternating between AA7075-T6 and Al-Cu-Li-T3 welding trials, the toolset was disassembled from the machine and etched in a 25% sodium hydroxide solution to fully remove residue aluminum.

Materials and Preparation

The materials selected for this study were AA7075-T6 and a developmental aluminum-copper-lithium material. AA7075 is an aluminum material whose primary alloying element is zinc. The Al-Cu-Li used is an ultra-high strength proprietary alloy whose chief alloying elements are copper and lithium. Both AA7075-T6 and the Al-Cu-Li used were nominally 1.24-mm thick. Cross-tension samples were cut to 50×145 mm with two 20-mm diameter holes spaced 100 mm apart. Lap shear samples were cut to 25×100mm. Sample geometries are shown in Figure 4. Immediately before welding, samples were scrubbed with an abrasive pad to remove oxides and wiped with an acetone-soaked towel.

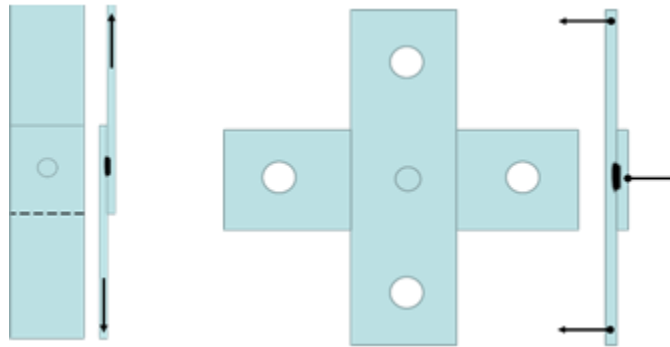


Figure 4. Lap Shear (left) and Cross Tension (right) Sample Geometries

Metallography and Mechanical Testing

Samples for microstructural evaluation were cut, mounted, and polished to a 9 micron finish following standard metallographic preparation procedures. After polishing, the samples were etched with a Kellers reagent for up to a total of 13 seconds in three immersion cycles. Polished and etched samples were examined with an Olympus BX51 microscope, up to 1000× magnification. A Zeiss Model EVO 60 scanning electron microscope (SEM) was used for high magnification examination of selected weld specimens.

Mechanical tests were performed in two configurations: lap shear and cross tension. For lap shear testing, samples were placed directly into the serrated grips of a universal tensile tester. Shims of appropriate thickness were used to ensure the samples would remain aligned to the pull axis. Cross-tension specimens were inserted into adapter tooling prior to being loaded into the grips of the universal tensile tester. Maximum load and displacement values were generated for each sample. All testing was completed in accordance with AWS C1.1.

Results

AA7075-T6 Results

Weld parameter development on the AA7075-T6 began with a focus on spindle speed and total cycle time. The matrix of parameters used for these initial trials is shown in Table 1. No clear pattern in tensile strength was noted, but a sudden change in failure mode from button to interfacial was observed between 1800 and 2100 RPM. Examples of these failure modes are displayed below in Figure 5. Based on macrographs shown in Figure 6, it was believed that the change in failure mode was related to break-up of the bond line at the edge of the weld. In order to improve weld quality in this region, a simple study was conducted to identify an appropriate rotating shoulder depth.

Table 1. AA7075-T6 Initial Parameter Window

RPM \ Cycle Time	Tensile Strength (kN)		
	1.9 sec	2.2 sec	2.5 sec
1500	4.5*	5.5	5.5
1800	4.0	4.0	4.5
2100	4.0	3.5	4.5
2400	4.0	5.5	5.0

**Reached tester capacity for low setting without failure.*

Interface Failure
Button Failure

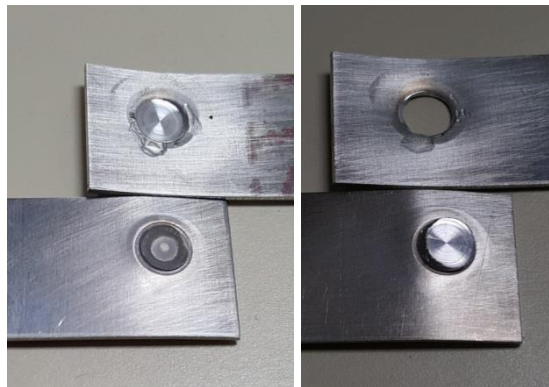


Figure 5. Interface Failure (left) and Button Failure (right)

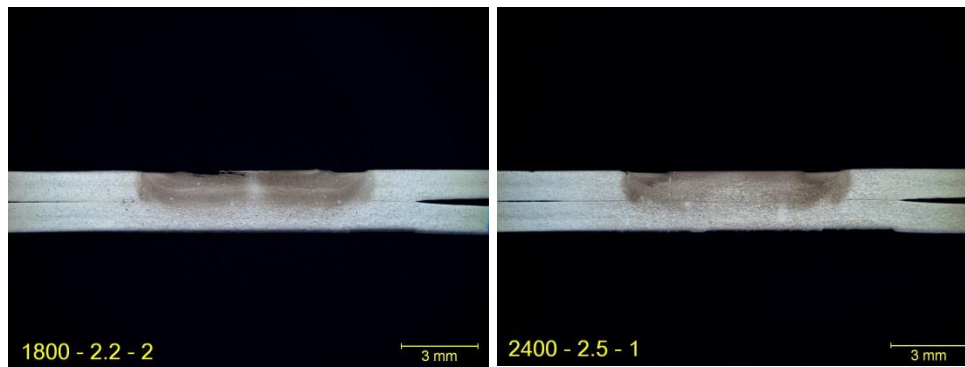


Figure 6. Macroscopic Comparison of Welds Made at 1800 (left) and 2400 (right) RPM

Welds were made at 2400 RPM, with a consistent weld time of 2.2 seconds. The plunge depths used were 0.1, 0.2, and 0.3 mm greater than the thickness of the top sheet of material. Weld macros and lap shear specimens were removed for all three plunge depths. Results from this study are presented in Table 2 as well as (a) 1.34 mm (b) 1.44 mm (c) 1.54 mm Figure 7. The initial trials showed that button failures were driven by a deep lack of fill defect on the outside diameter of the rotating shoulder. Deeper plunge depths resulted in a larger lack of fill, reducing tensile strengths.

Table 2. Plunge Depth Results

Plunge Depth (mm)	Ultimate Tensile Strength (kN)	Failure Type
1.34	3.9	Interface
1.44	4.4	Button
1.54	4.0	Button

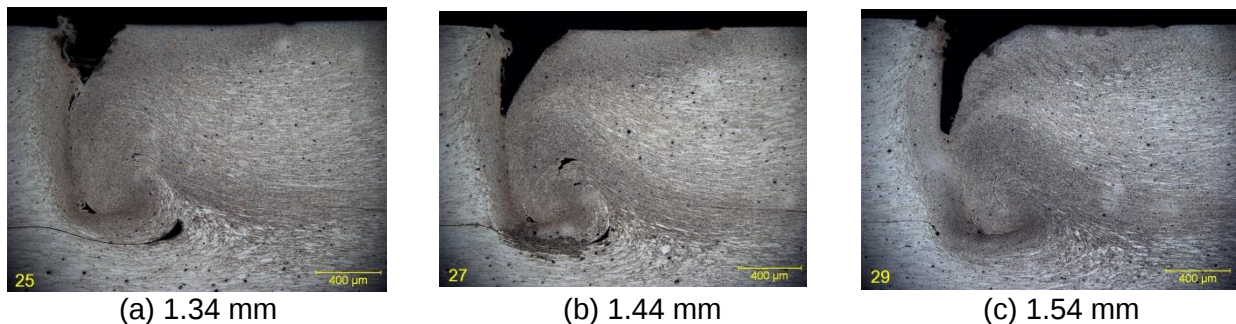


Figure 7. Macros Showing Increased Lack of Fill with Increased Plunge Depth

The first plunge depth study showed that improvements to the weld surface consolidation were required. An iterative development process was used to adjust the final height of the rotating shoulder and pin such that no deep crevice was left around the circumference of the weld as seen in Figure 7. The best case was found by overdriving the pin at the end of the weld sequence, causing a slight divot to form in the center of the weld and slightly pronouncing the weld edges under the rotating shoulder. A final short, downward movement of the rotating shoulder forged the raised ring back to the level of the plate surface and refilled any crevices that may have otherwise remained. The final weld schedule is shown in Table 3. As a result of the modified weld schedule, the ultimate tensile strength of the AA7075-T6 welded at 1800 RPM

increased from 3.6 to 6.4 kN. A comparison of the edge fill before and after optimization is displayed in Figure 8.

Table 3. AA7075-T6 Weld Schedule for Improved Consolidation

Time (s)	Spindle RPM	Shoulder Pos. (mm)	Pin Pos. (mm)
0.2	1800	0	0
1.0	1800	1.34	-1.31
1.0	1800	-0.102	0.1
0.2	1800	0.0	0.0

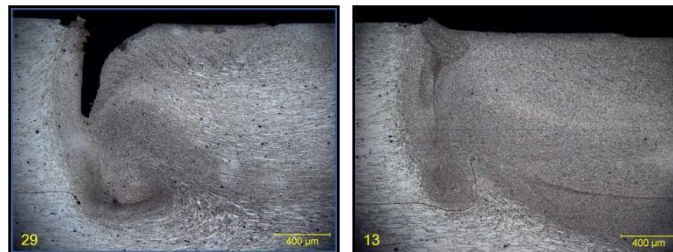


Figure 8. Edge Fill before (left) and after (right) Weld Schedule Optimization

A second plunge depth study was performed at 1800 RPM, using the improved weld schedule and the same plunge depth target values as the previous study. Five lap shear, five cross tension, and one macrographic specimen(s) were created at each of the plunge depth levels. Average tensile test results from this study are shown in Table 4. Inspection of weld macros showed that increased plunge depths were more effective at disruption of the bond line, but resulted in a decrease in joint strength. A weld time of 2.4 seconds, spindle speed of 1800 RPM, and plunge depth of 0.1 mm greater than the top sheet thickness were down selected as best-case parameters for the AA7075-T6 welds. This resulted in average lap shear strength of 6.4 kN, and cross-tension strength of 2.1 kN, giving a ductility ratio of 0.33.

Table 4. AA7075-T6 Plunge Depth Study Repeat

Average Tensile Results			
Plunge Depth	+1 mm	+2 mm	+3 mm
Lap Shear	6.4 kN	4.3 kN	4.3 kN
Cross Tension	2.1 kN	1.8 kN	1.6 kN

Vicker's hardness testing was done on the cross section of the down-selected AA7075-T6 welding conditions, the results of which are shown below in Figure 9. All material underneath the stationary shoulder of the tooling was considered to be in the heat-affected zone (HAZ). The AA7075-T6 showed a large area of softened material in the HAZ and thermo-mechanically affected zone (TMAZ). An increase in hardness was noted in the stir zone (SZ), creating a metallurgical notch on the circumference of the weld.

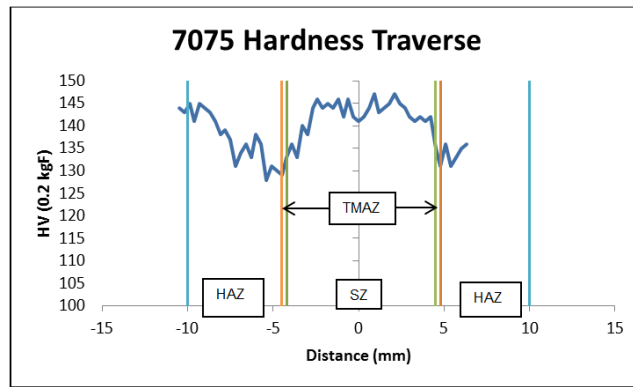


Figure 9. AA7075-T6 Hardness Traverse

Al-Li-Cu Results

Preliminary welding trials using the Al-Li-Cu material focused on finding an acceptable RPM range. This was necessary as literature searches on the FSSW of aluminum-copper-lithium alloys yielded no published results. Overall weld schedules were copied from the previously discussed work in AA7075 and altered as necessary. Plunge depth and weld time were held constant at 0.1 mm greater than top sheet thickness and 2.2 seconds, respectively. Spindle speed was varied between 1500 and 1900 RPM. Data scatter was more pronounced at lower RPM, and shear strength higher at greater RPM. This can be seen in Figure 10.

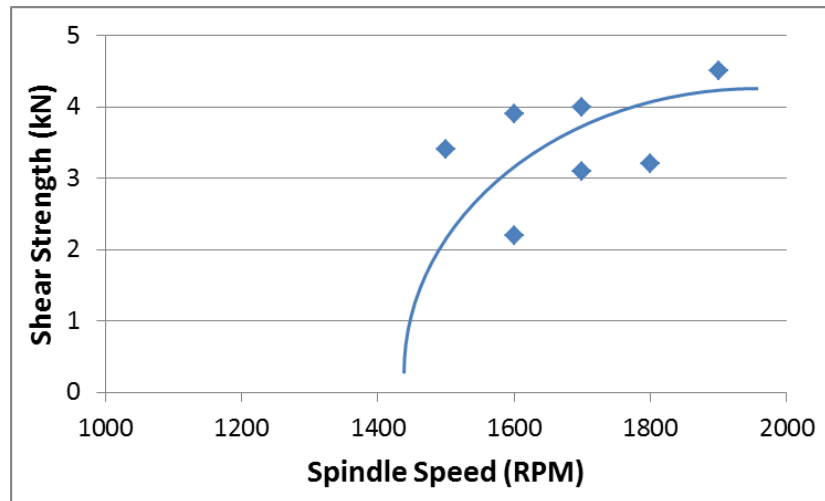


Figure 10. Initial Al-Cu-Li Trials

Based on the results found in initial trials and from AA7075-T6 parameter development, a matrix of RPM and plunge depth was used to down select final weld conditions. The improved weld schedule for fully consolidated joints was used to carry out the matrix. The spindle RPM was varied from 1800 to 2800 RPM, and plunge depth from 0.1 to 0.3 mm greater than the top sheet thickness. Lap shear and cross-tension specimens were made at each condition in order to drive selection of final parameters. The weld matrix with joint strengths is included in Table 5.

Table 5. Al-Cu-Li T3 Parameter Matrix with Lap Shear (left) and Cross-Tension (right) Strengths

Lap Shear Strength		Tensile Strength (kN)			Cross-Tension Strength		Tensile Strength (kN)		
RPM	Plunge Depth	+0.1 mm	+0.2 mm	+0.3 mm	RPM	Plunge Depth	+0.1 mm	+0.2 mm	+0.3 mm
1800		5.0	5.5	5.5	1800		0.5	1.0	1.0
2300		5.5	6.0	4.5	2300		0.0	1.0	1.0
2800		5.0	6.0	5.0	2800		0.0	1.0	1.0

Interface Failure
Button Failure

A spindle speed of 1800 RPM and plunge depth of 0.3 mm greater than the top sheet thickness were down selected as best-case parameters due to their combination of lap shear and cross tension strength. The full parameter schedule is disclosed in Table 6. Comparison of the weld schedule for AA7075 (Table 3) and of the weld schedule for the Al-Cu-Li (Table 6) shows a nearly identical final recipe with only the final plunge depth of the rotating shoulder being different. Five welds of each configuration were made using the final weld schedule and submitted for mechanical testing. A cross section created with these conditions is displayed below in Figure 11. The appearance of the weld is similar to welds made using the AA7075-T6 parameters, though the plunge depth is slightly greater. This resulted in average lap shear strength of 3.3 kN, and cross-tension strength of 0.7 kN, giving a final ductility ratio of 0.21.

Table 6. Al-Cu-Li Down-selected Weld Schedule

Time (s)	Spindle RPM	Shoulder Pos. (mm)	Pin Pos. (mm)
0.2	1800	0	0
1.0	1800	1.54	-1.51
1.0	1800	-0.102	0.1
0.2	1800	0.0	0.0

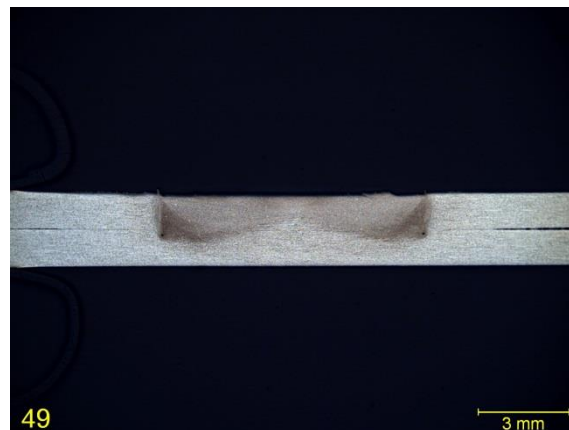


Figure 11. Macro of AL-Cu-Li Weld at Down-selected Condition

Vickers hardness testing was done on the cross section of a homogeneous Al-Cu-Li weld at the mid-thickness of the top sheet, the results of which are displayed in Figure 12. The Al-Cu-Li showed softening in the TMAZ and SZ. The stirred material was soft compared to that in the HAZ, and considerably softer than stirred material in AA7075-T6 welds. This is not unexpected, as the T3 temper is the forming temper of this product, not the final T8 temper which has comparable strength to the AA7075-T6 product.

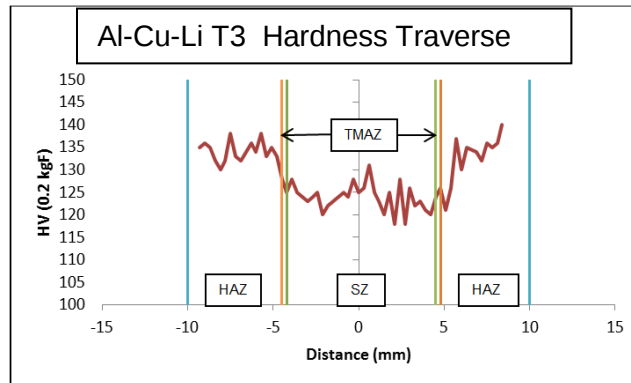


Figure 12. Al-Cu-Li-T3 Hardness Traverse

Examination of Fracture Surfaces

Fractures of the sidewall in button failures occurred in straight lines along the edge of the stir zone. Given the morphology of the failure, initial analysis indicated that some potential lack of bonding might have been present at the interface upon retraction of the rotating shoulder. Figure 13 contains an image of a failed lap shear specimen that was metallographically examined to determine fracture morphology. This cross section was taken in line with the axis of the pull test at the weld centerline. As a result of the test, two areas of stress were developed. Peak compressive stresses were accumulated on the left side of the image which shows complete fracture even through the lower sheet. Peak tensile stresses were accumulated on the far right side of the image and were the first areas to separate during testing, leaving the fracture surface intact.

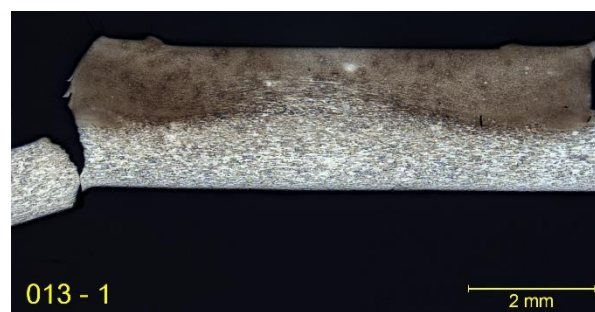


Figure 13. Button Failure of an AA7075-T6 Lap Shear Specimen

A 200 $\times$ magnification of a representative portion of the failure interface is displayed in Figure 14. The appearance of the sidewall, though vertical and following the edge of the weld, showed evidence of local ductility prior to failure, which indicated a uniform solid-state bond was present at the end of welding. This ductile appearance was found in both the nugget (Figure 14(a)), as well as the top sheet (Figure 14(b)). Examination of the weld toe (Figure 14(c)) at the bottom of the button failure on the right side of the weld showed crack propagation was simultaneously

occurring along the original faying surface. Appearance of the button failure was similar for the Al-Cu-Li alloy.

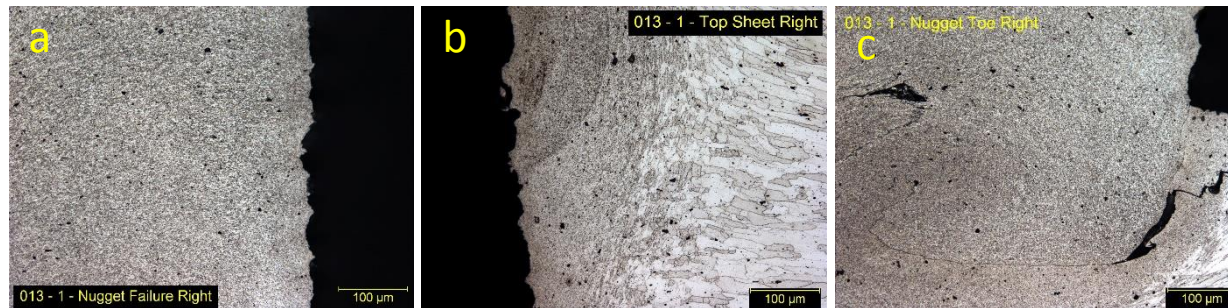


Figure 14. Close-up Examination of Tension Failure Interfaces in AA7075-T6

These observations were corroborated with direct examination of the failure surface with SEM. The tension side of an AA7075-T6 homogeneous weld nugget after button failure was examined in an SEM. A macro view of the sample shows a striated structure left from the withdrawal of the rotating shoulder (Figure 15(a)). Inspection of these striations at higher magnification revealed alternating bands of ductile failure and liquated surfaces. Regions of ductile failure (Figure 15(b)) presented typical cup-and-cone morphology. A distinctly different morphology was found in adjacent bands that were noted to possess a smooth, rounded profile (Figure 15(c)). This appearance is typically associated with a liquated microstructure which was not unexpected from this alloy and has been widely discussed in open literature. Bands of ductile failure and liquated regions alternated throughout the weld thickness to produce the striations that are clearly present in the macro view of the specimen. From a weld integrity perspective, the liquated regions were not deemed to cause a significant negative impact on the weld quality as they represented a minor fraction of the overall surface area with a predominately ductile failure mechanism.

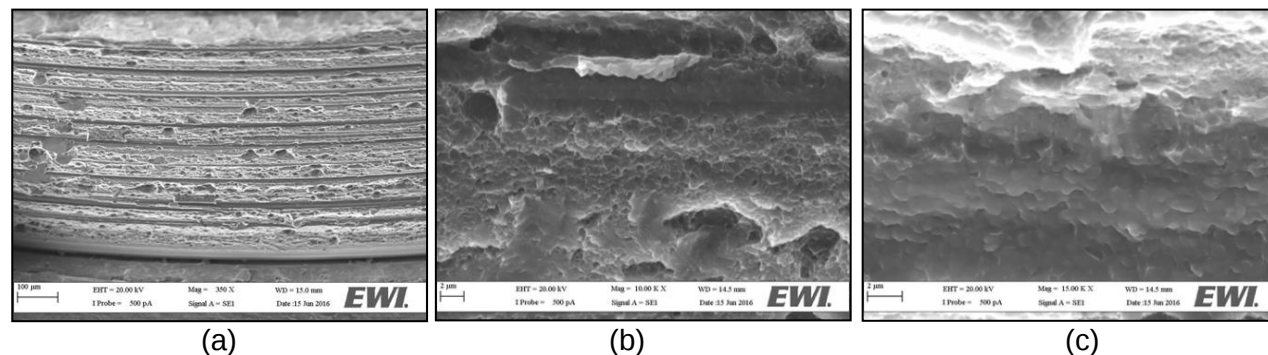


Figure 15. SEM Images of an AA7075-T6 Fracture Surface

Examination of the tension side of an Al-Cu-Li homogeneous weld nugget after button failure was likewise examined with a SEM. Unlike the AA7075-T6 specimen, no distinct banding was noted in the macro image (Figure 16(a)). Close examination of the fracture surface showed cup and cone failure throughout the weld thickness indicating ductile failure (Figure 16(b)). The lack of liquation on the fracture surface of the weld was unexpected. The aluminum copper lithium family of alloys is well known to present liquation phenomenon and was previously thought to be a significant contributing factor toward the low cross-tension strength values attained during welding.

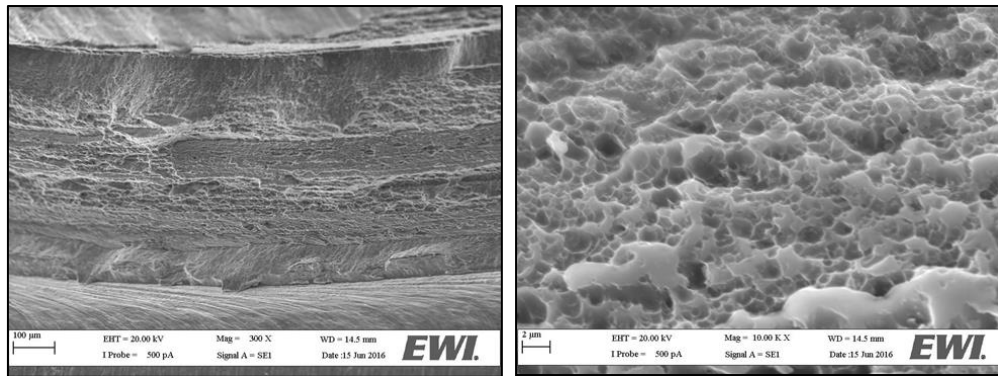


Figure 16. SEM Images of Al-Cu-Li Fracture Surface

Discussion

Mixed Mode Failures

Perhaps one of the most perplexing problems encountered in the course of the investigation was the inconsistent failure mode amongst weld coupons produced with identical parameter sets. A combination of interfacial and/or button failures was encountered for both material types. Convention with traditional resistance spot welding would favor the creation of a weld that always fails in a button mode. However, preferring this mode may not be practical with RFSSW. No correlations could be made between failure mode and higher or lower weld ultimate strengths.

Unlike conventional spot welding, RFSSW is a solid-state process that has more in common with friction welding at a fundamental level. Perhaps the most corollary effect is the difference in weld energy from the outside diameter, which has the greatest energy, to the centerline of the toolset, which has essentially no energy due to the lack of rotational velocity at this point. These effects have physical manifestations in the weld cross sections. In Figure 17 below, remnant faying surfaces can be noted extending from the centerline of the weld out to a short distance from the edge of the rotating pin and shoulder interface. Within the area of the rotating shoulder, severe plastic deformation of the lower sheet is noted as a result of the bulk movement of top sheet material. Remnant faying surfaces were present, but no longer continuous or able to be noted as having width. In fact, the tortuous path created is advantageous to assist in developing mechanical strength. The width of this area varied from weld to weld, but was able to be generalized as having similar dimensions to the top sheet thickness. With similar dimensions, the dominant failure mechanism was driven toward the portion of the weld containing a stress concentrator or susceptible microstructure.

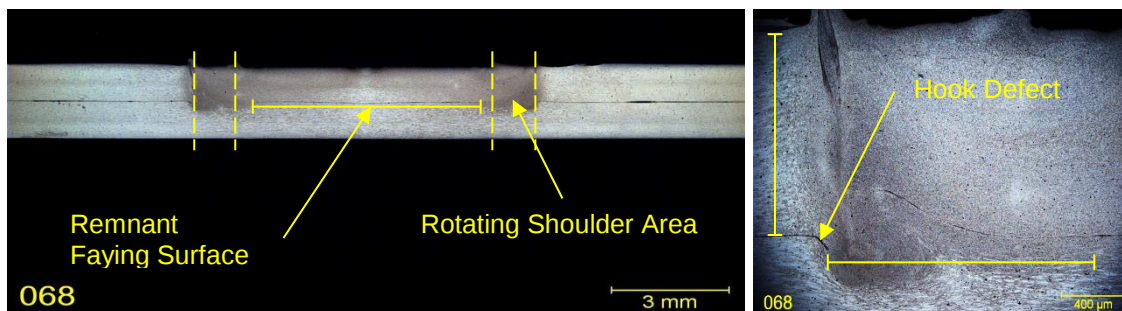


Figure 17. Diagram of Well-bonded Areas Within the Weld Zone

A secondary weld defect, a hook type, is common in RFSSW and can extend for significant distances into the area of the weld under the rotating shoulder. The hook defect is the result of an unstirred faying surface that is displaced by the toolset rather than being consumed by it. The effective weld area for interface failures was able to be determined as the area encompassed by the hook defect on the outside diameter (OD) of the weld nugget minus the area containing the remnant faying surface in the center of the weld, Equation 1:

$$A_{INT} = \pi r_{HOOK}^2 - \pi r_{REMNANT}^2 \quad (1)$$

Button-type failures occur along the vertical sidewall and most often coincide with the HAZ of the weld. Calculation of the effective weld area then becomes the plate thickness times the circumference of the weld, Equation 2. In some cases, the presence of other weld flaws such as circumferential lack of fill (Figure 7) was found to effectively act as sheet thinning causing an artificial lowering of the weld strength.

$$A_{BUTTON} = 2\pi r_{NUGGET} \times T_{TOPSHEET} \quad (2)$$

Using Equations 1 and 2, the effective weld areas for either an interfacial or button failure for the weld in Figure 17 was calculated using 4.4 mm as hook radius, 2.9 mm as the radius of the remnant faying surface, 0.05 mm as top sheet thickness, and 4.2 mm as weld nugget diameter. This gave an effective weld area of 33.6 mm² for an interfacial failure, and 33.1 mm² for a button-type failure. In order to drive the failure toward a button type, it would either be necessary to increase the size of the weld, or decrease the thickness of the plate. It should be noted that any increase to the plate thickness would necessarily drive the failure toward the interfacial type since the weld size is fixed, whereas the plate thickness may be varied up to 10 mm per the machine specification.

Effect of Tooling Temperatures

One important consideration that was found through the investigation was the importance of the starting temperature of the tooling, including both toolset and welding anvil. Though both parts were cooled with recirculating water, the distance between the cooling water jacket and the welding was up to 25 mm, leaving a substantial distance over which conductive heat transfer must be the dominant form of heat removal. Notes during welding indicate that several welds were required to bring the toolset up to temperature before consistent, steady-state results could be achieved. Effects of taking weld samples from outside of the steady-state conditions were noted to affect surface and sub-surface consolidation as well as ultimate weld strength values. It became standard practice to perform three to five warm-up welds prior to accepting any weld specimens for analysis such as metallography or mechanical testing and also to minimize time between productions of weld coupons for repetitive testing.

As discussed in the procedure, it was necessary to use two separate anvils to produce cross tension and lap shear samples. For the lap shear samples, a simple fixed copper anvil with integral cooling channels was used, resulting in fast cooling rates to room temperature following welding. The anvil to produce the lap shear specimens was, in contrast, a more massive piece of copper, but was cooled through secondary contact with a mating piece of copper that was directly water cooled. The cooling rate for this anvil was slower, with more time required to reach room temperature after welding. In order to directly compare joint strengths produced using the two anvils, five lap shear specimens of Al-Cu-Li were made on each type. Figure 18 shows a comparison of the strengths from this test. As can be seen, welds produced on the directly water cooled anvil possess twice the ultimate strength of welds produced on the

indirectly water cooled anvil. The Al-Cu-Li was intentionally used for this test, given the inherent heat sensitivity of the material. As previously shown in the hardness results, the Al-Cu-Li material was soft in, and adjacent to, the weld. Slower cooling rates increased the amount of over aging, softening the weld region and decreasing the material's strength. Similar testing on the AA7075-T6 material was not found to significantly affect the results. It is expected that the T8 temper of the Al-Cu-Li material would exhibit similar characteristics as the AA7075-T6 material.

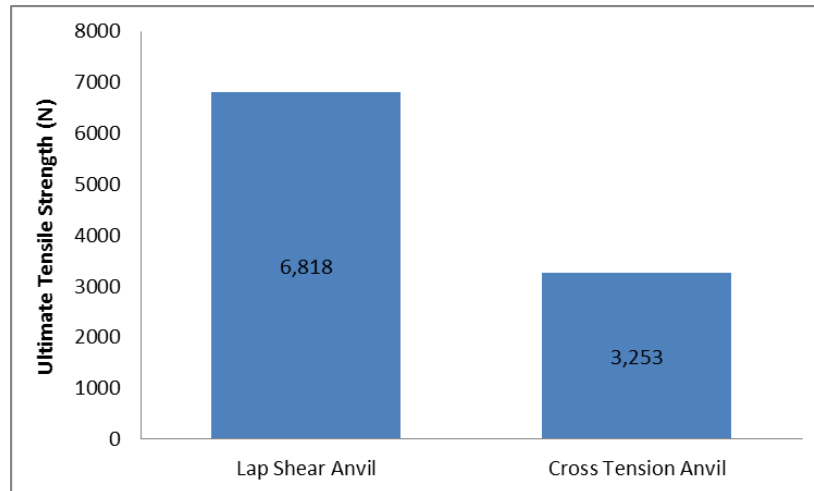


Figure 18. Lap Shear Strength Comparison Using the Two Anvils

Conclusions

In this study RFSSW was examined as a method for joining aluminum lithium and aluminum zinc alloys. Welds were successfully made and tested Joints were evaluated using mechanical testing and metallurgy, leading to the following conclusions:

- 1) Best practice welds in AA7075-T6 were made with a 2.2 second weld time, 1.34 mm plunge depth, and rotation speed of 1800 RPM. At these conditions, lap shear strengths of 6.3 kN and cross-tension strengths of 2.1 kN were achieved.
- 2) Best-practice welds in the Al-Cu-Li were made with a 2.2 second weld time, 1.54 mm plunge depth, and rotation speed of 1800 RPM. At these conditions, weld strengths of 6.8 and 0.6 kN were achieved in lap shear and cross tension, respectively.
- 3) Examination of weld fracture surfaces showed evidence of minor liquation present in the AA7075-T6 and no liquation present for the Al-Cu-Li aluminum copper lithium alloy.
- 4) The cause of mixed mode failure among groups of identical parameters was investigated and found to be related to the effective shear areas that are almost identical between interfacial and button failures for this material thickness and toolset diameter.

Recommendations

In order to reduce metallurgical notches due to hardness profiles, it is recommended that a post-weld heat treat be investigated. This could reduce the amount of over aging of precipitates that occurs during the weld cycle. In turn, joint performance in cross-tension loading has the potential to be increased. Investigations of anvil temperature on weld strengths should be further investigated for welding of the Al-Cu-Li that experienced a reduction in mechanical properties after exposure to reduced weld cooling rates.

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