



## Dissimilar Friction Stir Spot Welding of Aluminum to Steel For Use in the Automotive Industry

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## **Abstract**

### **Objectives**

The main objective of these experiments was to investigate the feasibility of using a laser deposited tool to successfully weld Aluminum to steel provided by General Motors (GM). To do this, first welds were made to determine whether refill Friction Stir Spot Welds could be made between aluminum and steel. Next, process parameters should be optimized to produce the strongest weld possible. Finally, the tool should be analyzed to ensure that minimal wear is occurring during the welding process.

### **Findings**

It was found that refill welds made are comparable to other Friction Stir Spot Welding (FSSW) techniques. It was found that stronger bonds were possible using a shoulder plunge sequence and electro-galvanized steel. Future work will include changing the location and material of the laser deposition on the tool and further analyzing the parameters of welding.

## **Introduction**

### **Background**

Friction Stir Spot Welding (FSSW) is a developing solid-state welding technique that can form strong bonds between metals previously considered “unweldable.” FSSW has been done using many different tools and techniques. Pin tools, flat tools, refill options have all been studied for welding one type of metal to itself. When dissimilar metals are welded together, the differences in properties of these metals introduce unique difficulties in joining. Many traditional forms of welding cannot be used to bond dissimilar metals and the material differences can lead to issues with joining techniques such as Resistance Spot welding, Riveting, and even Friction Stir Spot Welding.

## **Objectives**

In these experiments, an aluminum alloy was friction stir spot welded to steel using a refill FSSW technique. There have been several studies in which an aluminum alloy was friction stir spot welded to steel, however, published work on a refill technique could not be found. The main problems associated with welding aluminum to steel are the difference in melting points of the two metals, and the tendency of aluminum and steel to form intermetallic compounds even at relatively low temperatures. These compounds are usually very brittle compared to the base metals used in welding and often cause a weakening in the joint. Another common issue is the difference in hardness of the two metals.

Usually aluminum alloys are FSSW together using a steel tool, but if a steel tool was used to weld steel, the tool would wear excessively. Harder materials that can be used to friction weld steel are very expensive. In this study, a steel tool with a laser deposition of tungsten carbide in a nickel matrix was used in an effort to develop a cheaper tool to make the FSSW of aluminum to steel feasible in the automotive industry.

## **Broader Impact**

The automobile industry has been attempting to decrease the weight of vehicles to improve fuel efficiency. To achieve this, high strength aluminum alloys have been used to replace steel portions of the car frame. [Sun et. al, 2013] This problem has propagated a myriad of solutions including resistance stir welding [Zhang et. al., 2011], self-piercing rivets [Lout et. a. 2011], ultrasonic stir welding [Haddadi et. al. 2012], etc. Each technique has advantages, and each comes with unique difficulties.

Friction stir spot welding is an attractive option for several reasons. Firstly, FSSW uses a fraction of the energy needed for other welding techniques. There are no dangerous fumes that are formed as a byproduct of FSSW so no special environments or safety equipment is needed. In addition, spot welding techniques such as Self Piercing Rivets and Resistance Stir Welding need consumable materials, or extra materials that are used up during the process so they cost more by adding the cost of not only the machinery and the extra energy, but also the continuing cost of the consumable products.

FSSW was first used in the automobile industry by Mazda. Mazda used this technique to weld the back door panel to the rest of the car. For this project, GM will use the FSW technique to weld an aluminum roof sheet to the side pieces of the car. The spot welds will bond the piece of aluminum to a Resistance Spot Weld between three sheets of steel. RSW is a feasible technique for welding steel to steel, but because of aluminum's properties, RSW for aluminum causes one electrode for RSW to degrade very quickly.

FSW is also used in the aerospace industry. Because FSW is a solid state welding technique, pieces can be welded together without a great loss in properties from the base metal. For this reason, FSW is commonly used to replace riveting for aluminum pressure vessels, such as aircrafts.

## **Procedure**

### **Materials**

Aluminum 6022 alloy

GMW2M-ST-S-CR-EG60G60G-E (cold rolled, electro-galvanized steel)

Tungsten Carbide (in nickel matrix)

### **Equipment**

Spot Welding Machine (AMP Center SDSM&T)

Laser Deposition Machine (AMP Center SDSM&T)

MTS 858 Mini Bionix II (Tensile Machine)

ZEISS SUPRA 40VP Scanning Electron Microscope  
LECO PR- 25 Hot Mount Press

## Procedures

For these experiments aluminum alloy was spot welded to steel using refill friction stir spot welding techniques. Aluminum 6022 alloy and cold rolled steel were the materials welded and were provided by General Motors. The steel was supplied in both electro-galvanized and non-galvanized forms and both were welded, tested, and compared. Before a non-galvanized (uncoated) material was received, an attempt was made to scrapethe zinc coating off of the galvanized steel. The results from welds made with the scraped steel are shown along with the others.

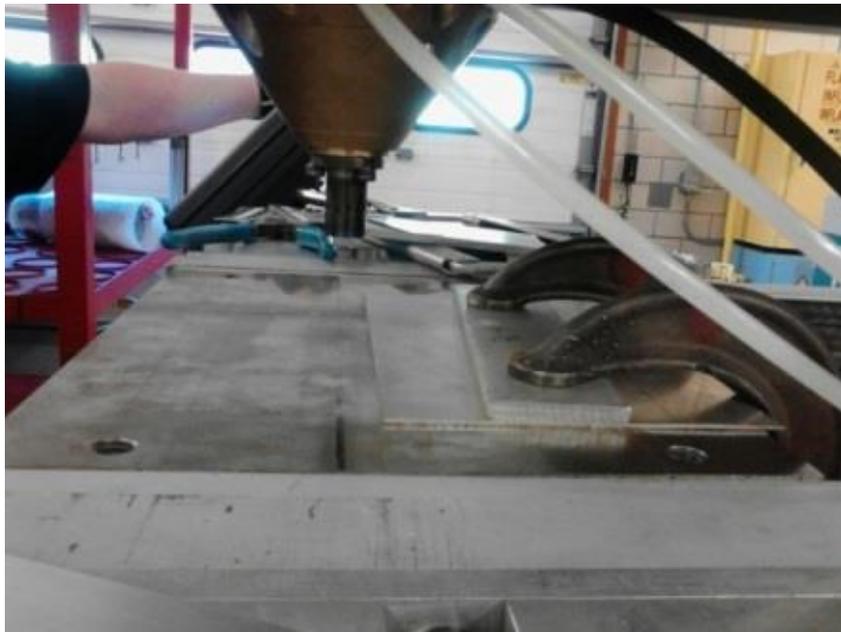


Figure 1: FSSW Machine

The tool used was a purchased tool provided by the AMP center at SDSM&T made of steel. A tungsten carbide compound in a nickel matrix was deposited on the pin of the tool using laser deposition. The idea behind this tool is that the tungsten carbide (WC) deposit will be

inserted into the steel during welding while the remainder of the tool will remain solely in the aluminum sheet. Because of this, cheaper tools can be used because it is not necessary that the entire tool be made of an expensive, harder-than-steel, material.

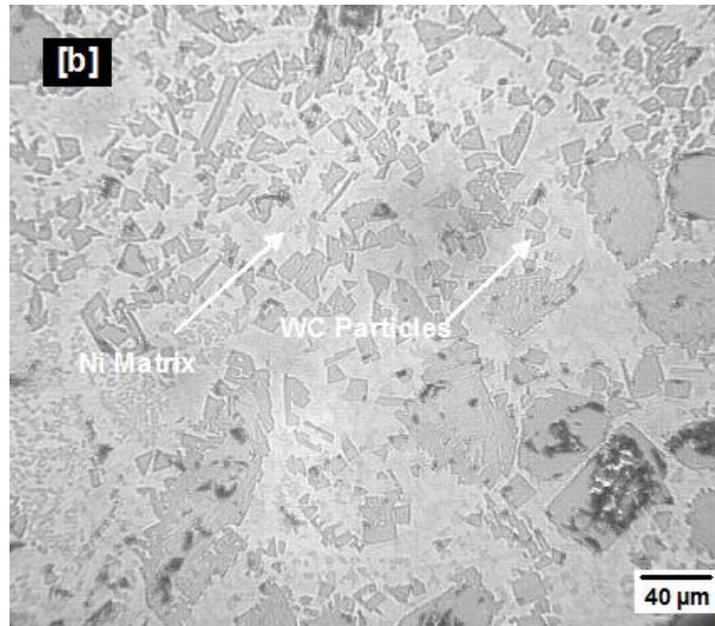


Figure 2: WC in nickel Matrix provided by Dr. Bharat Jasthi

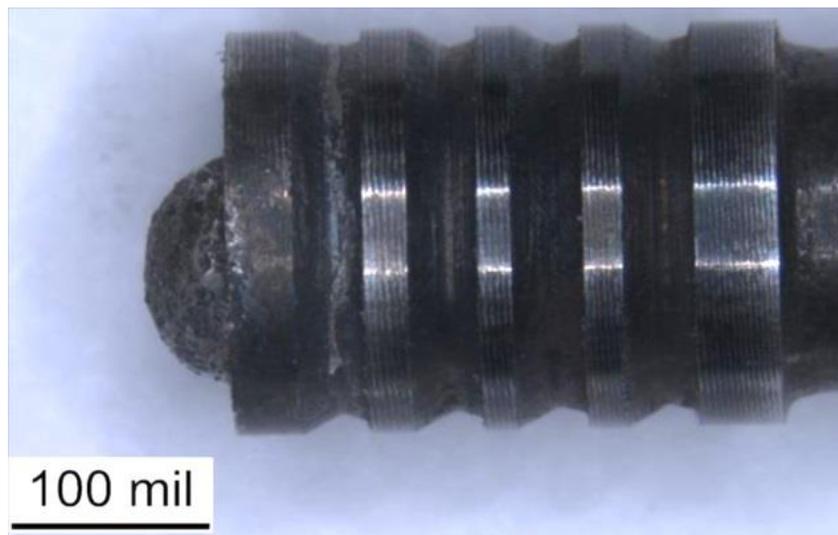


Figure 3: Tool pin with laser deposition provided by Mr. Todd Curtis

Welds were made using Al 6022 as the top sheet and steel as the bottom. A sleeve plunge sequence lasting 3.93 seconds and a pin plunge sequence lasting 2 seconds were used

with the tool having the laser deposited nub of tungsten carbide (WC) in a nickel matrix on the pin. The speed of the spindle was 2200rpm during the welding. Since no tungsten carbide was present on the shoulder of the tool, the shoulder plunge weld did not penetrate the steel. During the pin plunge sequence, the tungsten carbide nub entered the steel and the rest of the tool remained in the aluminum.

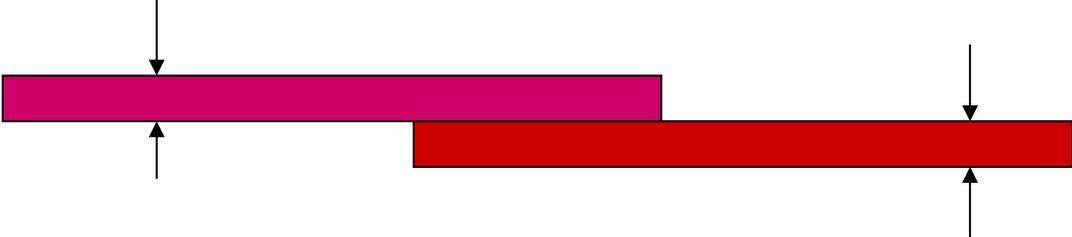


Figure 4: Lap configuration of Aluminum and Steel sheets

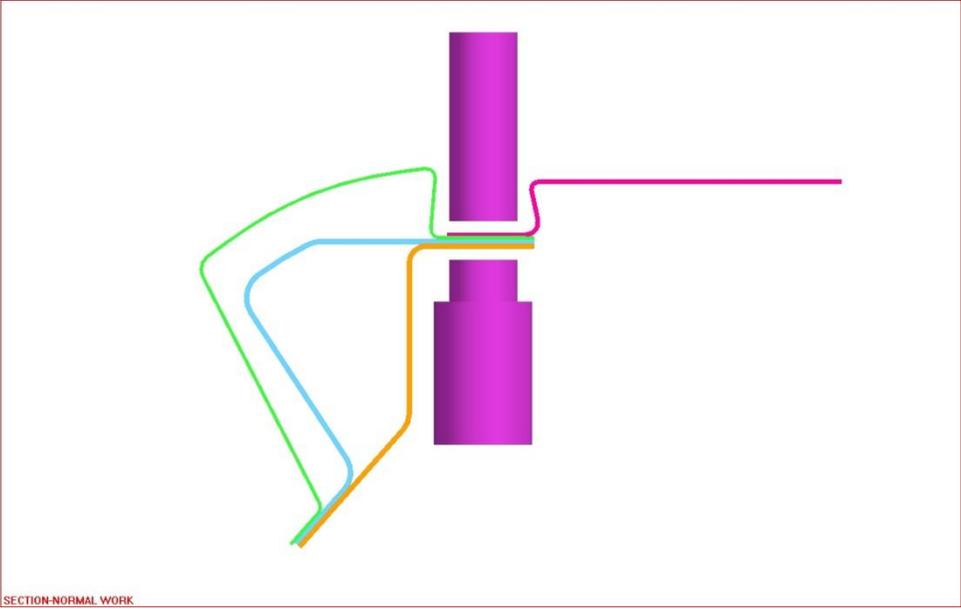


Figure 5: Part configuration courtesy of General Motors

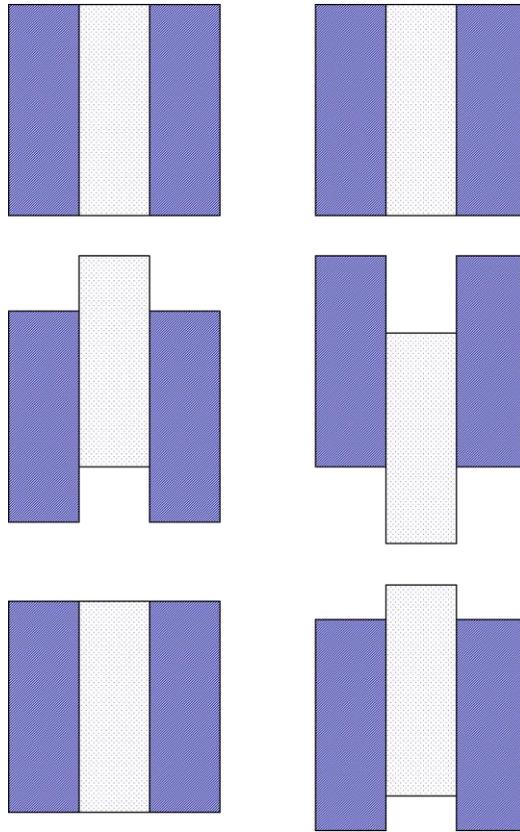


Figure 4: Simplified Weld sequence shoulder and pin plunges

Table 1: Welding Parameters

Pin Plunge Sequence				Sleeve Plunge Sequence			
Time [sec]	Spindle n[1/min]	Sleeve Travel mm	Pin Travel mm	Time [sec]	Spindle n[1/min]	Sleeve Travel mm	Pin Travel mm
0.00	400	-1.00	-1.00	0.00	300	-1.00	-1.00
0.50	2200	+0.00	+0.00	0.27	2200	+0.00	-0.60
1.00	2200	-0.40	+0.75	0.83	2200	+0.90	-1.68
1.00	2200	+0.02	-0.04	0.83	2200	+0.00	+0.00
0.50	2200	+0.00	+0.00	1.00	2200	+0.01	-1.00
				1.00	2200	-1.50	-1.86

Tensile samples were tested using the MTS tensile machine in the AMP center. When the samples were loaded, spacers were used to ensure that the load was applied parallel to the weld. Samples were pulled at a rate of 0.1 inches/min and the stress/strain curve was recorded

and the ultimate strength of the weld was returned. The machine is programmed to stop automatically when the sample breaks.



Figure 5: MTS tensile tester pulling a sample

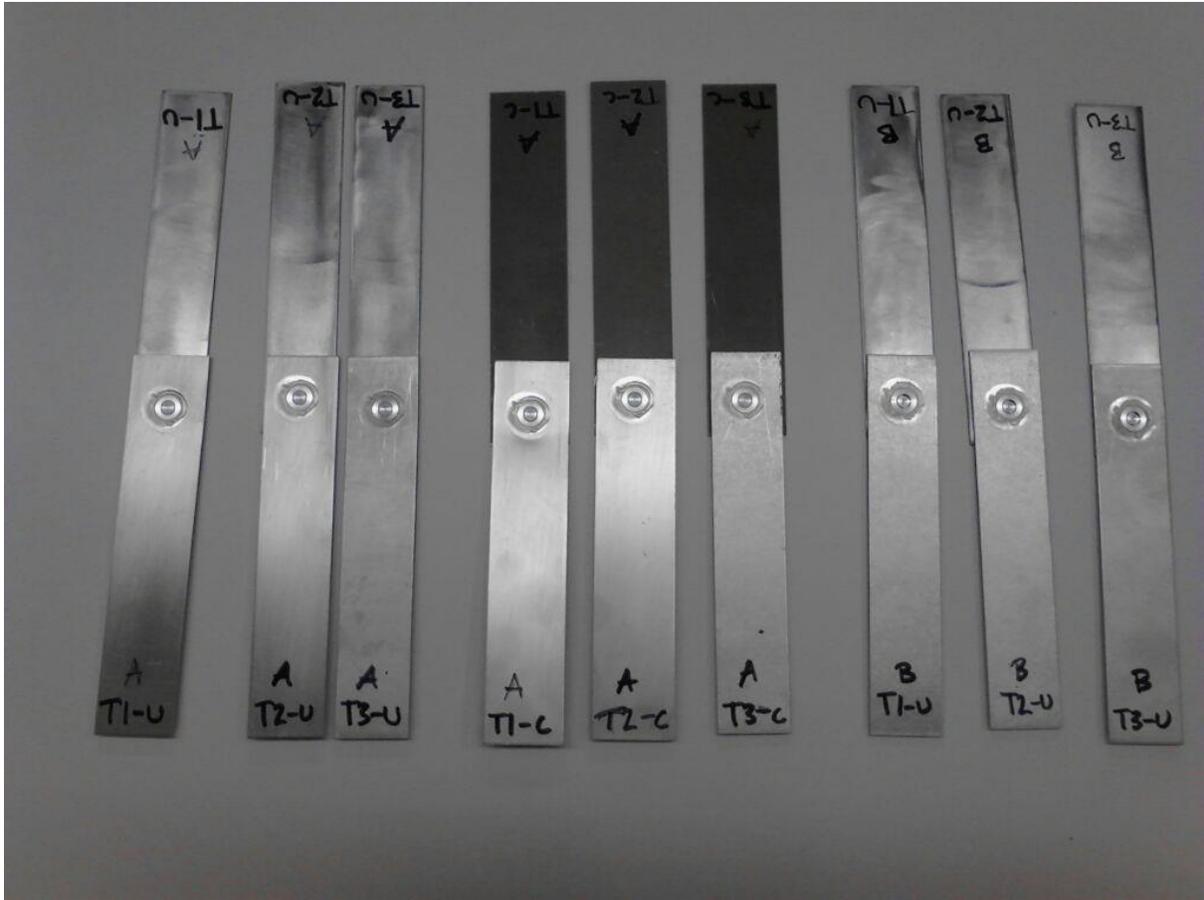


Figure 6: Tensile Samples to be tested

Weld analysis samples were cut using a wet saw and then machined using a milling machine to cut the weld as close to the center as possible. Samples were hot or cold mounted into a polymer and polished to 0.5 microns using LECO equipment. The aluminum was etched using a sodium hydroxide solution or a hydrofluoric acid solution and the steel was etched using a nitol solution labeled as 3% nitol. It was difficult to polish and etch the samples effectively because of the difference in material properties. A microscope and the Scanning Electron Microscope (SEM) were used to take close up pictures of the weld cross-sections.

The SEM analysis was performed using ZEISS SUPRA 40VP Scanning Electron Microscope. Two macros were used in the SEM. Both were shoulder plunge samples, one weld was made using the galvanized steel and the other was made using the uncoated steel. The weld

made with the uncoated steel was unetched when placed in the SEM but the aluminum had been etched with the sodium hydroxide solution. The uncoated sample was examined to see what mixing had occurred between the aluminum and steel while the galvanized sample was examined to see what had happened to the zinc coating during welding. Both samples were checked for a visible intermetallic layer.

## **Results**

### **Welding**

During welding there was a severe problem with the tool sticking to the welded material. A hammer was required to knock each sample off of the welding machine. In addition, the sticking problem was worst with the electro-galvanized steel using the pin-plunge sequence and no samples with these parameters could be successfully produced. The main theory behind the cause of the sticking suggests that the affinity between nickel and steel causes the atoms to exchange places easily within their crystal structures, so the laser deposition was sticking to the steel. Another theory is that the softened metal cools when it is pushed up into the void left by the pin or the shoulder and subsequently sticks to the inside of the tool (Badarinarayan et al. 239). In previous refill FSSW attempts where sticking was a problem, a “fixed-position” refill FSSW often had less sticking issues than the “shoulder-first” refill FSSW technique used in this study (Badarinarayan et al. 239). In the future, it is advisable to try other refill FSSW techniques and parameters as well as new material for the laser deposition to reduce and hopefully eliminate the sticking problem. After severe sticking, excess material was cleaned off of the tool by welding aluminum to aluminum.

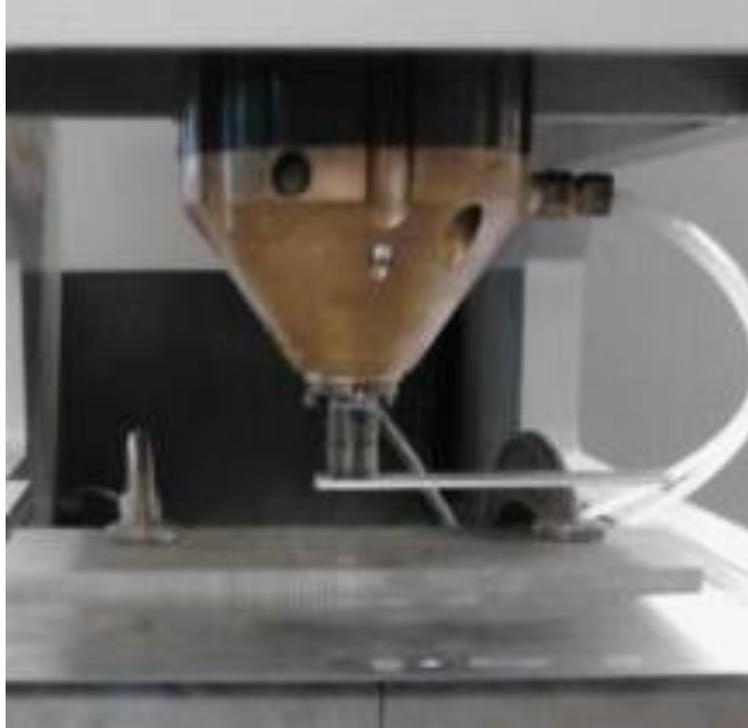


Figure 7: Weld sticking to FSSW machine

When the cross sections of the welds were examined, it was seen that the steel was being stirred up by the laser deposition on the pin of the tool. Pieces of steel can be seen with the naked eye and the macrographs of the pin-plunge welds.

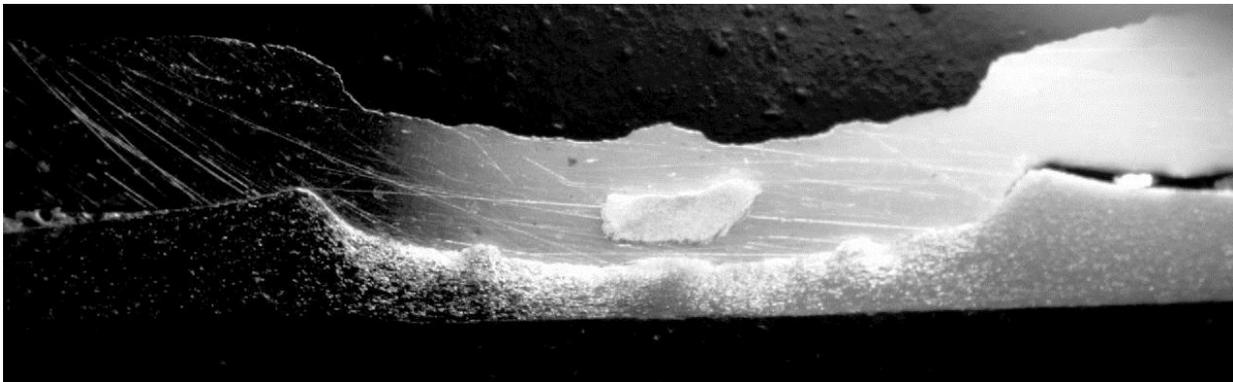


Figure 8: FSSW pin plunge made with scraped steel

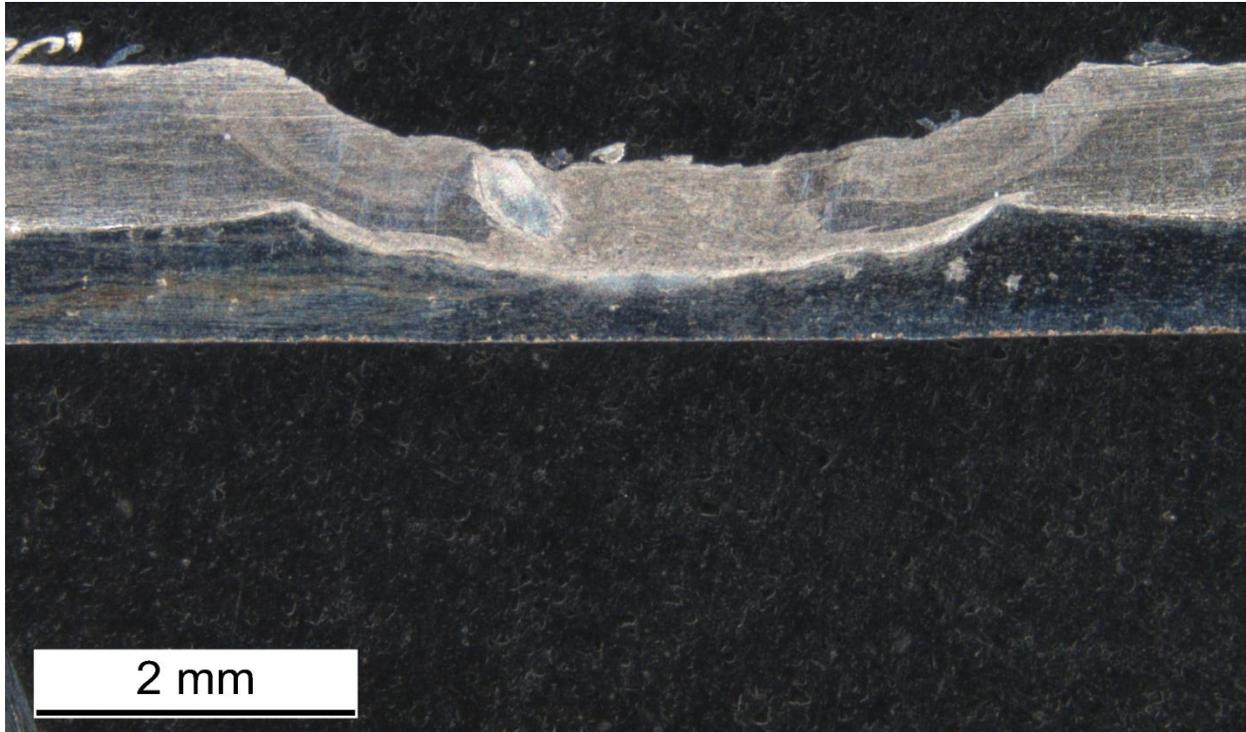


Figure 9: FSSW pin plunge made with uncoated steel

Some thinning of the aluminum sheet can be seen as well in both the pin-plunge and shoulder plunge samples. This is common for spot welds made with high rotational speeds and greater plunge depths [Badarinarayan et al., 253].

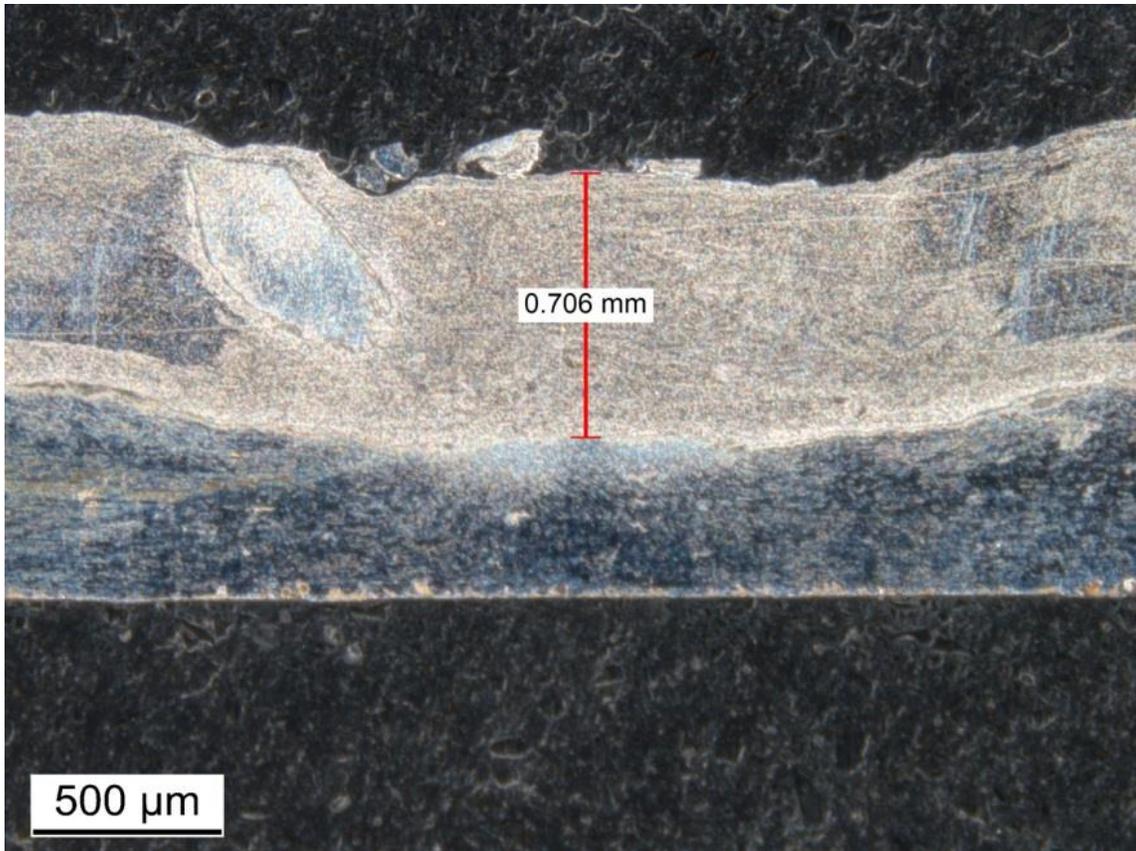


Figure 10: FSSW showing thinning of aluminum sheet

No visible deformation of the steel can be seen in the macros of the shoulder plunge samples. However, the interface between the aluminum and steel is more jagged in the uncoated sample. The fragments of steel visible beneath the steel sheet in the uncoated sample are the result of flash from the milling machine.

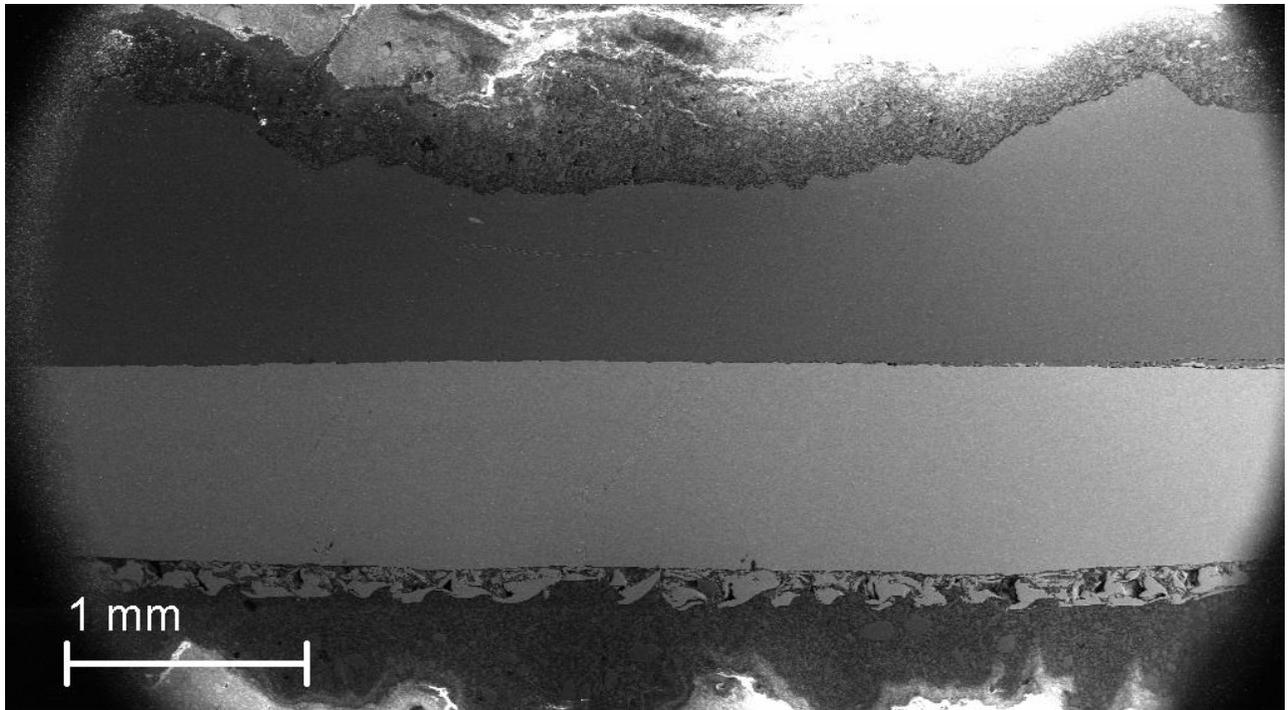


Figure 11: FSSW shoulder plunge with uncoated steel

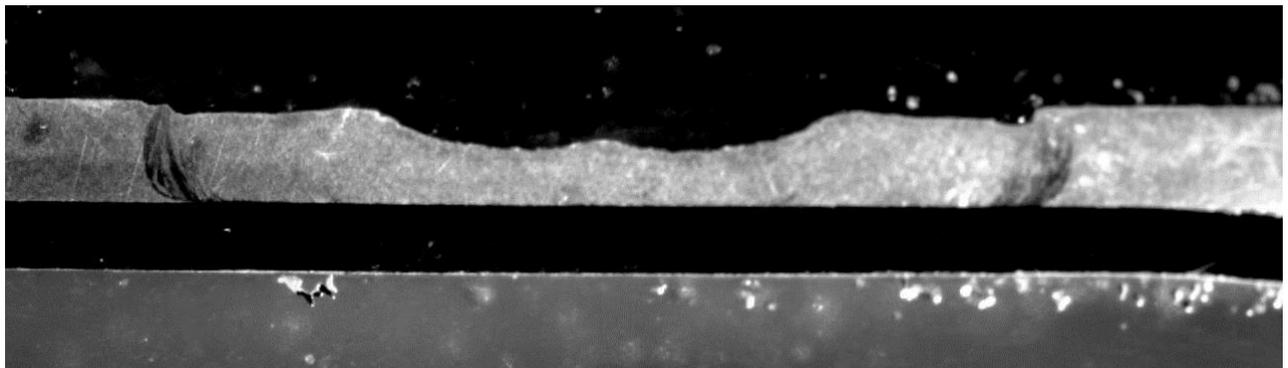


Figure 12: FSSW shoulder plunge with electro-galvanized steel

### **Mechanical Properties**

Three or four samples of each weld type were produced and tensile tested. It can be seen that the strongest bond was formed between the aluminum alloy and the scraped steel using the shoulder plunge sequence. The aluminum welded to the electro galvanized steel with the shoulder plunge sequence was able to withstand the next highest ultimate tensile load and the other results can be seen on Table 2. The weakest bond was formed with the non-galvanized

steel using the pin plunge sequence. Unfortunately, the galvanized and non-galvanized steel could not be compared with the pin plunge weld. The sticking problem made it impossible to produce a successful pin-plunge weld with the electro-galvanized steel.

Table 2: Average ultimate tensile loads for each weld type

Weld type	Ultimate tensile strength	
Shoulder plunge with galvanized steel	618 ± 12 lbf	2.75 ± 0.06kN
Shoulder plunge with uncoated steel	533 ± 15 lbf	2.37 ± 0.07kN
Pin Plunge with uncoated steel	350 ± 26 lbf	1.56 ± 0.12kN
Pin plunge with galvanized steel	Welds were not completed or tested due to the sticking of the tool to the material	
Shoulder plunge with scraped steel	764 ± 14 lbf	3.4 ± 0.06 kN
Pin Plunge with scraped steel	552 ± 52 lbf	2.4 ± 0.23 kN

The welds made with the scraped steel were able to bear the highest loads. The tensile samples broken also had significantly more deformation than the other samples before. It is unlikely that the process of scraping the zinc off of the steel made the steel hot enough to change the properties of the steel, so possible reasons for these results include that a very thin layer of zinc remained on the steel and that the sheet was thinned by the scraping process which made more deformation possible.

All of the shoulder plunge samples failed by shear failure of the aluminum to steel interface. The tensile samples made from the scraped steel using the pin plunge method also exhibited shear failure along the aluminum-steel interface. The pin-plunge samples made with the uncoated steel, however displayed a “nugget pullout” failure.

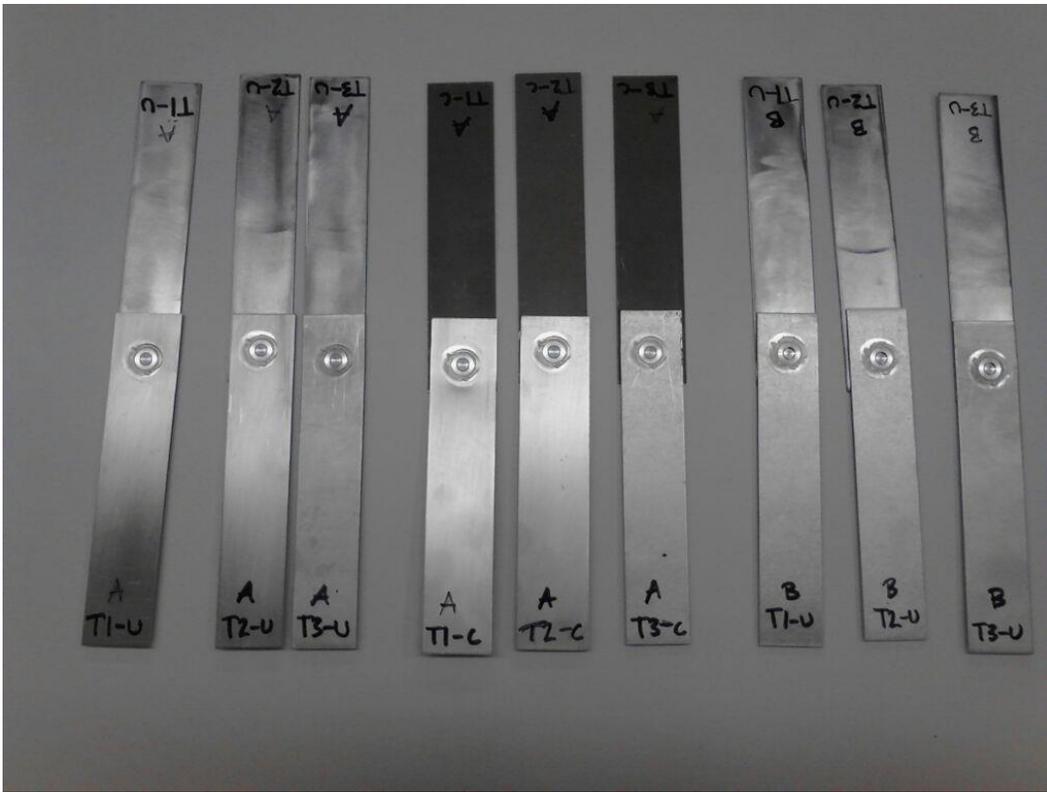


Figure 13: scraped and coated steel FSSWs



Figure 14: scraped shoulder plunge tensile samples after failure

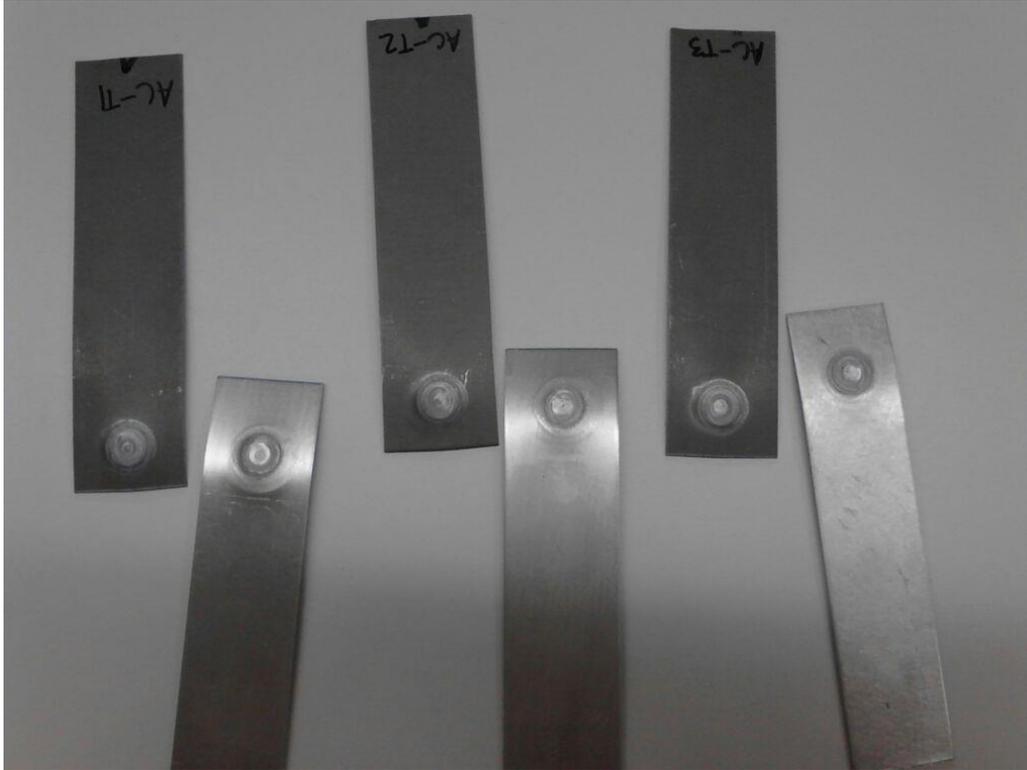


Figure 15: electro-galvanized shoulder plunge tensile samples after failure

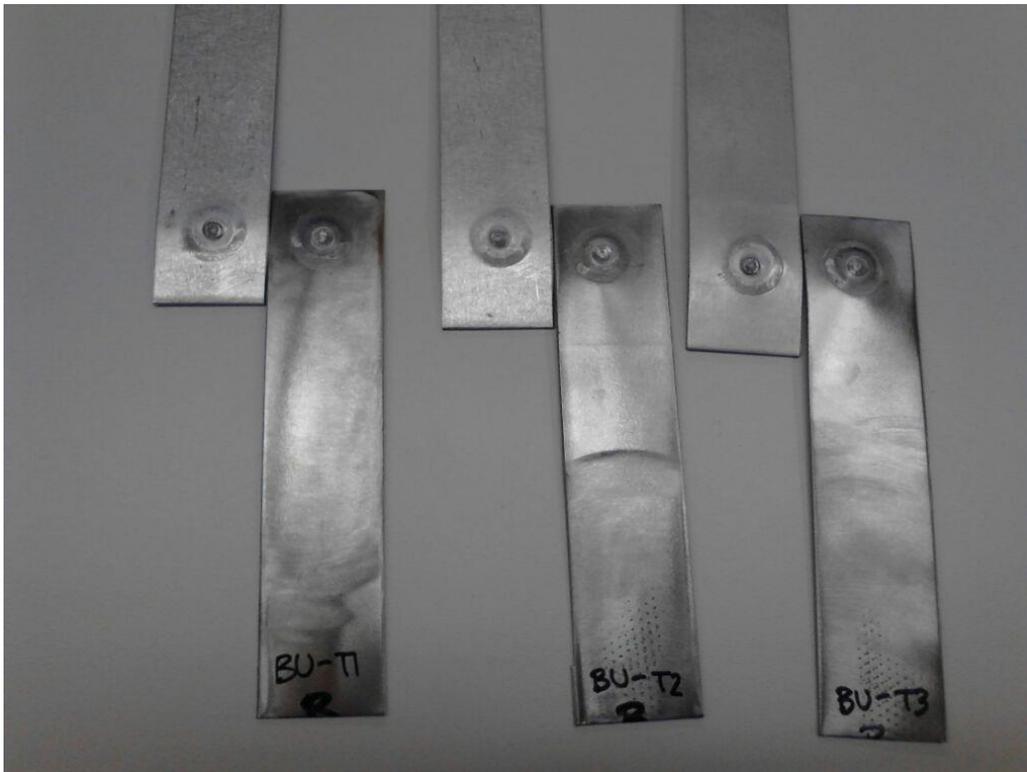


Figure 16: scraped pin plunge tensile samples after failure

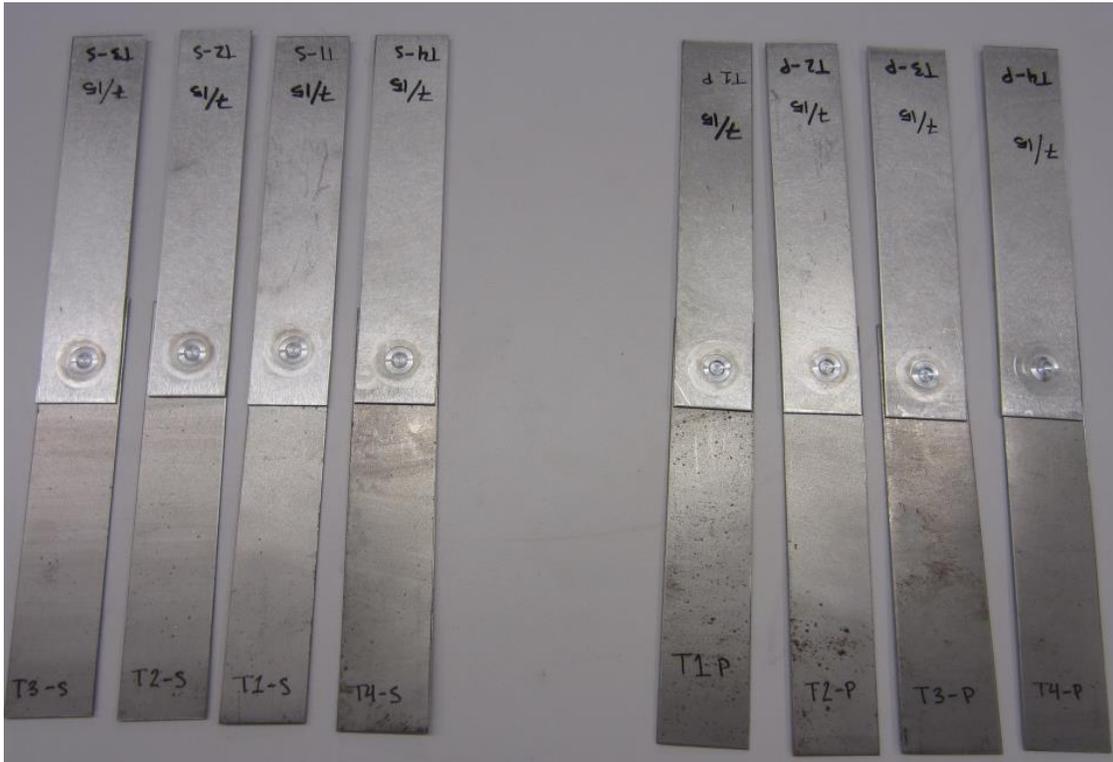


Figure 17: Uncoated Shoulder and pin plunge tensile samples before testing

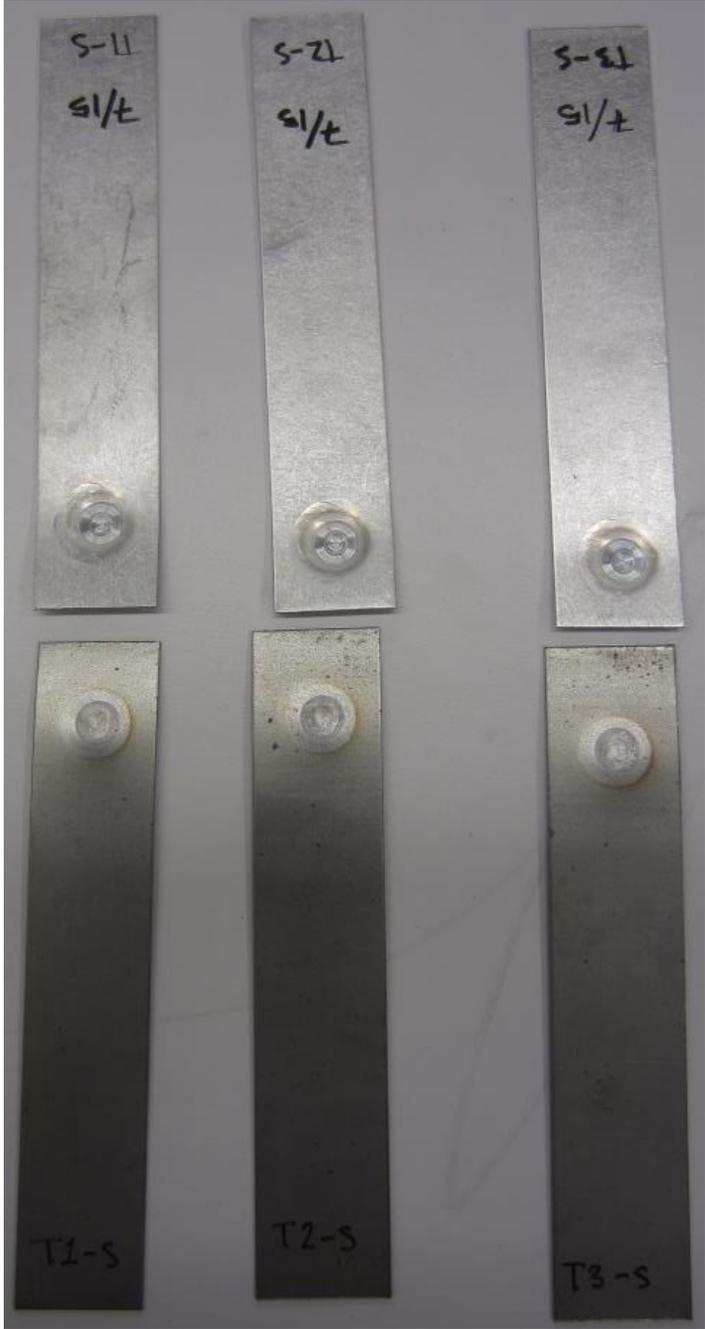


Figure 18: Uncoated shoulder plunge tensile samples after testing



Figure 19: Close up of uncoated shoulder plunge tensile samples shear failure mode



Figure 20: Uncoated pin plunge tensile samples after testing



Figure 21: Close up of pin plunge sequence with uncoated steel tensile sample failure mode

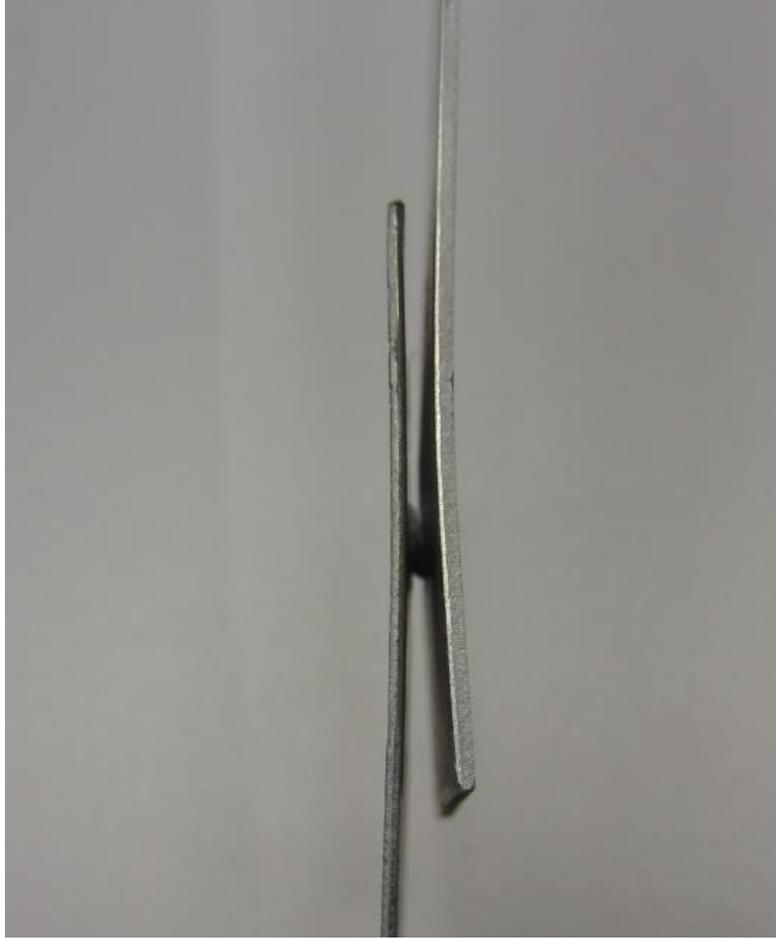


Figure 22: Side view of pin plunge sequence with uncoated steel tensile failure mode

### **SEM Analysis**

Two samples were observed in the Scanning Electron Microscope. Both were welded using the shoulder plunge sequence, one sample used the galvanized steel and the other used the uncoated steel. No intermetallic layer of 500nm or greater could be detected on either sample.

In the sample with the uncoated steel, it could be seen that there was some mixing of the steel into the aluminum even though the tool did not enter deep enough into the sample to enter the steel. Small particles of steel of about one  $\mu\text{m}$  could be seen in the aluminum. This could be an effect of the welding process; however, the steel particles are small enough that they could have been scraped up into the aluminum during the polishing process.

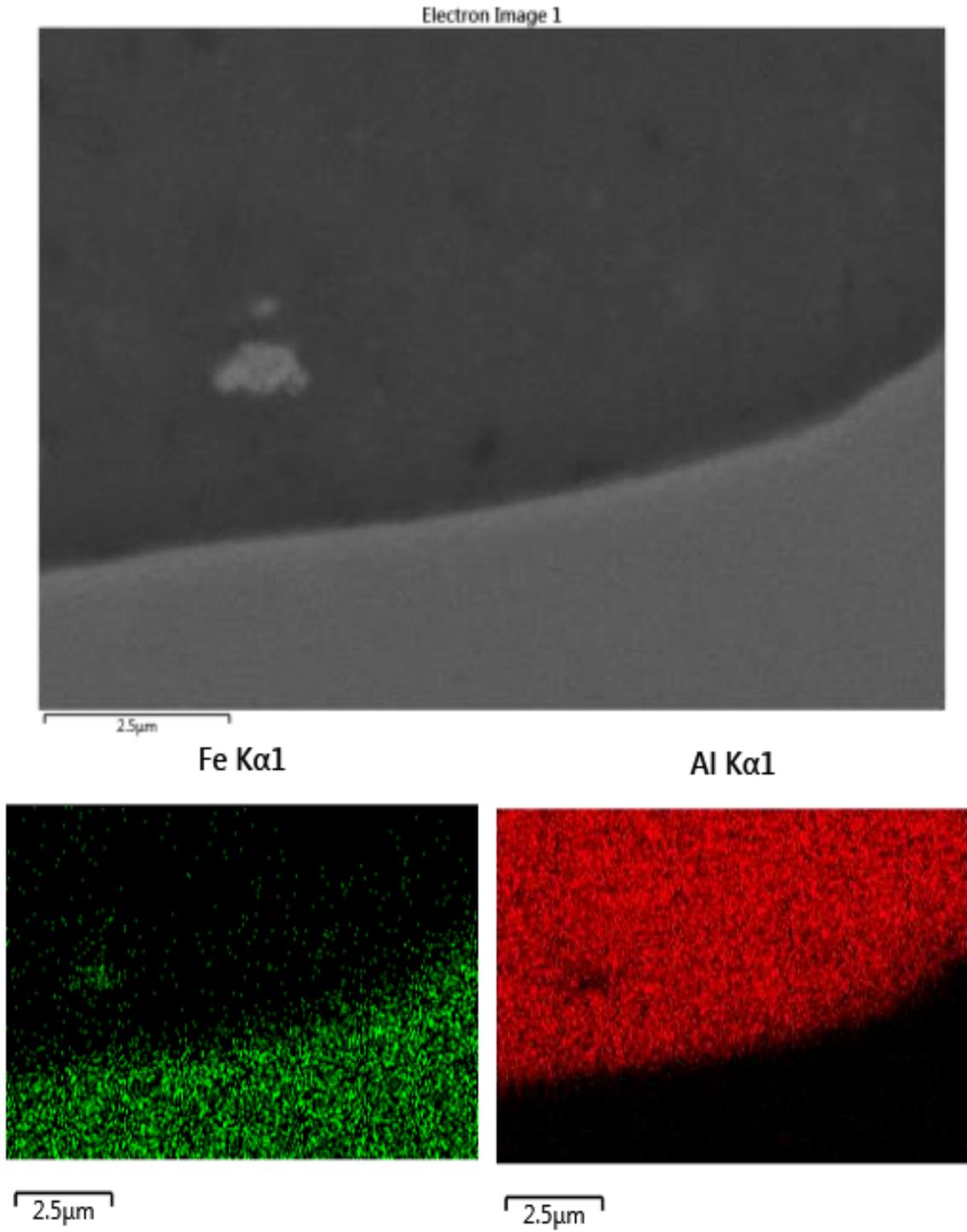
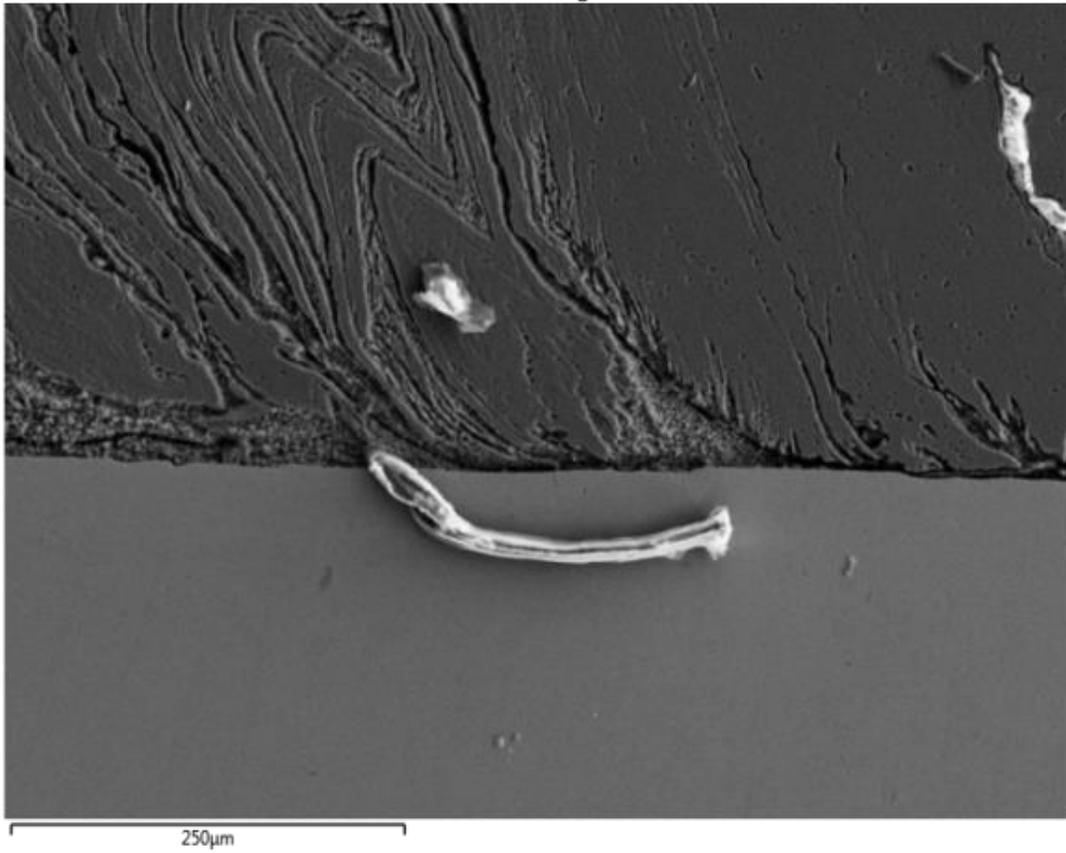


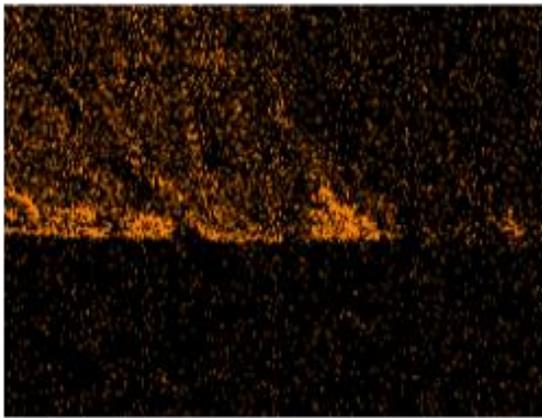
Figure 23: SEM and EDS images of shoulder plunge sequence with uncoated steel Al-steel interface

With the galvanized steel, there was no mixing of the steel into the aluminum. However, it could be seen in the EDS (Energy Dispersive Spectroscopy) that the zinc coating was being pushed out of the middle of the weld and up into the aluminum on the sides of the weld. This interlocking of the zinc into the aluminum could be the reason for the stronger welds between the galvanized steel and the aluminum vs. the uncoated steel and the aluminum.

Electron Image 5



Zn Lα1\_2



EDS Layered Image 5



Figure 24: SEM and EDS images of shoulder plunge sequence with galvanized steel left side of weld (there is a piece of lint in the shot. Please disregard)

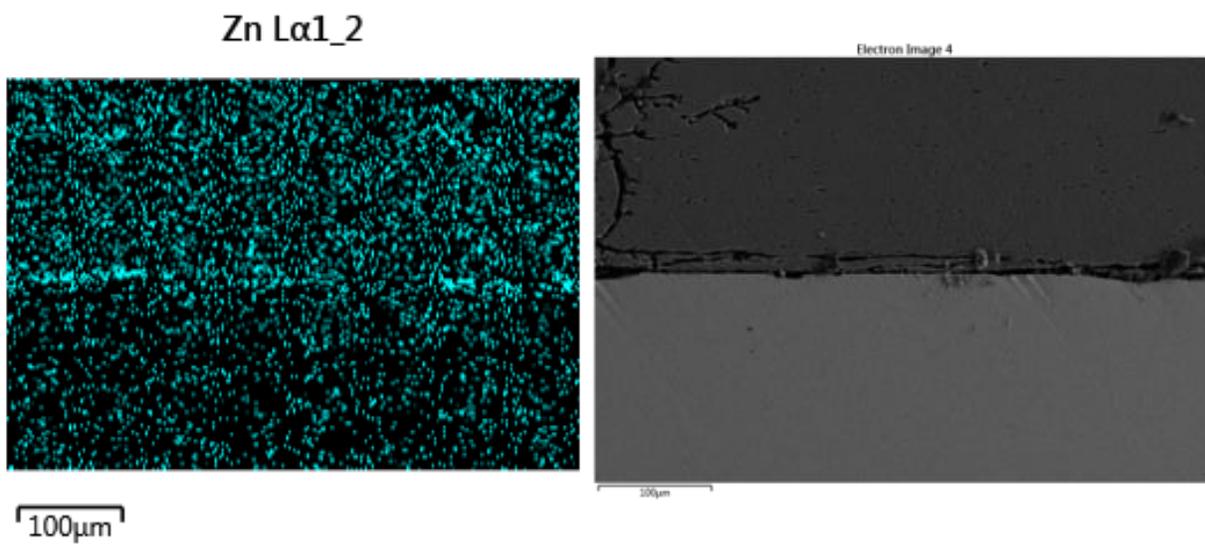
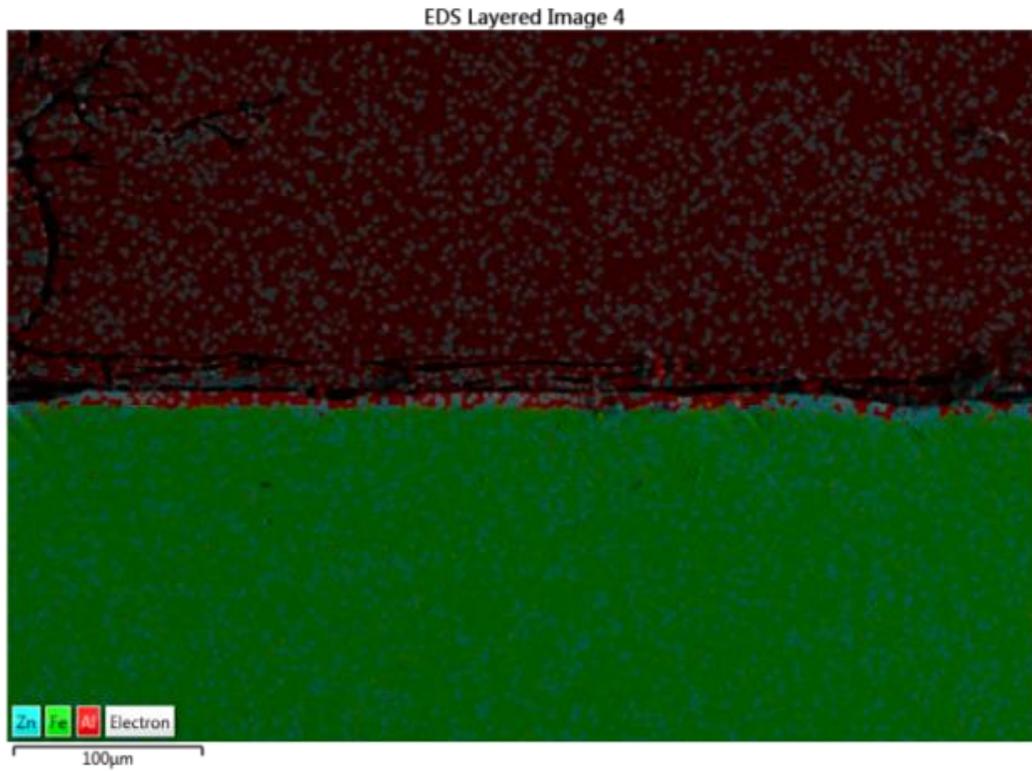
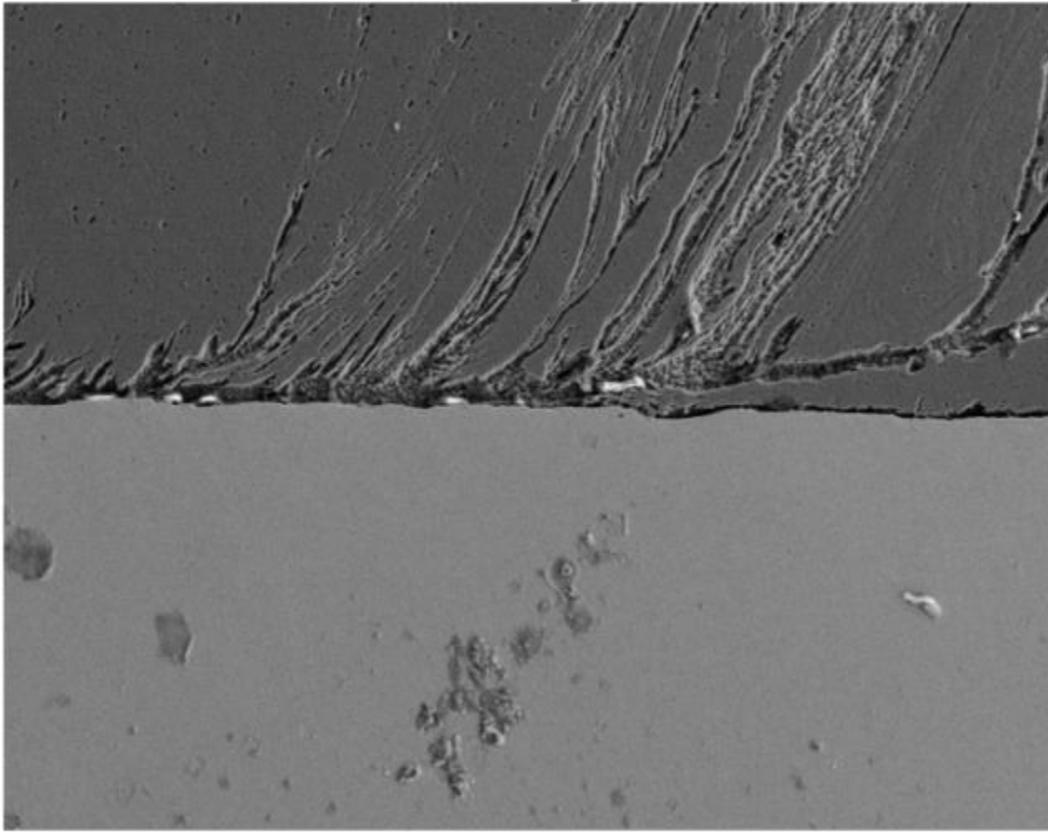
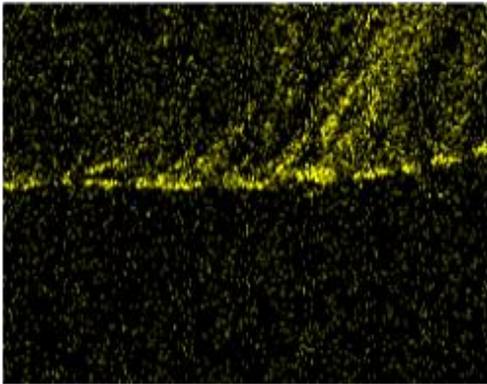


Figure 25: SEM and EDS images of center of weld made with shoulder plunge sequence with galvanized steel

Electron Image 3

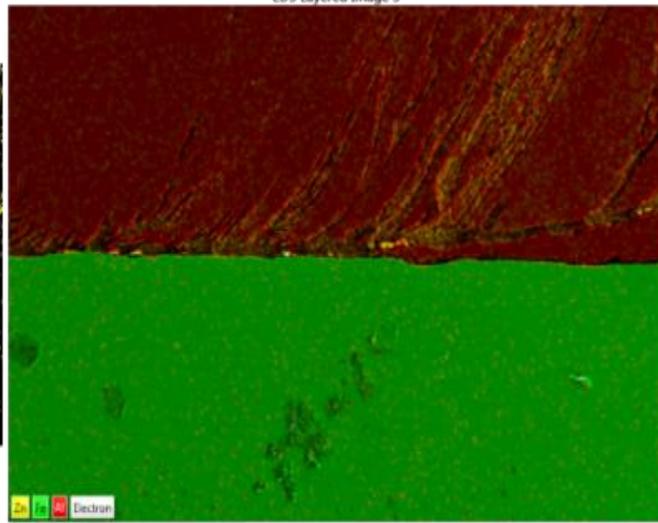


250µm  
Zn Lα1\_2



250µm

EDS Layered Image 3



250µm

Figure 26: SEM and EDS images of shoulder plunge sequence using galvanized steel right side of weld Al-steel interface

## Discussion

Table 3: Strengths of associated spot welds

Material type and Thickness (mm)	Weld Type	Max Strength (kN)	Reference
Al 6016 (1.2mm) / IF-steel (2mm)	FSSW	4.5	Bozzi et. al. 2010
Al 6111 (1.15mm) / DP600 steel (1.8mm)	FSSW	2.4	Liyanage et. al., 2009
AA6061-T6(2mm) / DP780 Steel(1.25mm)	SPR	6.5	Lou et al. 2013
AA6061-T6(2mm) / DP780 Steel(1.25mm)	Electroplastic SPR	7.3	Lou et al. 2013
AA6111 (1mm) / DX56-Z coated steel (1mm)	Ultrasonic spot welding	3.5	Haddadi et al. 2012
AA6008 (1.5mm) / H22YD galvanised steel (1mm)	RSW	3.3	Zhang et al. 2011
AA5754 (1.8mm) / DP 980 steel (1.4mm)	Friction Bit Joining (FBJ)	6.3	Miles et al. 2009
AA6016(T6) (1.1mm) / DC04+ZE Steel (0.9mm)	Fluxless Laser beam joining	9.8	Laukant et al. 2006
AA 6022 (1mm)/ EG low carbon steel (0.7mm)	FSSW	2.75	Made and tested in AMP center

Welds were made with comparable properties to other FSSW attempts, but the results were still lower than those found when using techniques such as self-piercing rivets. Ultimately, it is desired that spot welds reach 90% of the strength of a FSSW bond formed between two sheets of aluminum. More parameters need to be adjusted and welds between aluminum sheets must be tested as well to determine if such strengths are being reached.

## Conclusions

### Summary

Successful refill friction stir spot welds were made between the aluminum alloy and steel and the mechanical properties were comparable to other welds between aluminum and steel.

From the macrographs of the pin plunge sequence welds, it can be seen that the steel was stirred up by the tool and mixed in with the aluminum. There was no detectable wear on the tool after welds were made, so with further testing, the use of a scribe tool for FSSW in the automotive industry could be termed feasible.

From the macrographs of weld cross sections, it could be seen that the laser deposition was mixing up the steel into aluminum. No deformation of the steel could be seen in the macrographs of the shoulder-plunge samples, however.

Small particles of steel could be seen in the aluminum layer in the SEM for welds made with uncoated steel and a shoulder-plunge sequence. Those particles could not be seen in welds made with the electro-galvanized steel; however it could be seen with the EDS analysis that the zinc was being scraped out of the center of the weld area and to the outside during the welding process. No intermetallic layer greater than 500nm could be detected in either sample.

## **Recommendations**

Due to the sticking problem, the material of the laser deposition should be changed to a different material to reduce the sticking. Since the stronger bonds were made with the shoulder plunge sequence and the steel was successfully stirred up by the laser deposited material, a new tool with a laser deposition on the shoulder is desired.

## **Future Work**

Future work should also include an analysis of the failure planes especially on the samples that displayed what appears to be a nugget-pullout failure mode. Further analysis of the effect of the zinc coating on galvanized steel should also be conducted. Since this FSSW will

eventually be placed atop a RSW between three sheets of structural steel, welds should be made on the RSW to see which properties (if any) are affected.

The effects of the new laser deposition material and location should also be recorded carefully to help achieve the strongest weld possible. In short, more welds should be made in order to optimize parameters and ensure that the strongest weld possible is being utilized in industry.

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