Friction Stir Lap Welding Aluminum to Steel Using Scribe Technology

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Abstract

In this study done for General Motors, a tool equipped with a scribe was used to determine the feasibility of friction stir lap welding 6022 aluminum and low carbon electro galvanized steel alloy panels 1.0 mm and 0.7 mm respectively. The welds were made to determine if the friction stir welding technique could be used within the automotive industry. Three tools were designed with different scribe geometries. Tool design differed in the diameter of the scribe, the distance from the center of the scribe to the center of the pin, and the number of scribes used. Two travel speeds were tested, 20 IPM and 30 IPM and the advancing and retreating side of the weld were altered to see if these parameters affected the mechanical and microstructural properties. Microstructural characterization was done by optical macroscope and scanning electron microscopy. Tensile lap shear tests were conducted for mechanical property evaluation. Results show “Hooking” features were present in the welds, the retreating side being the most severely affected. Traveling at 20 IPM and having the aluminum top sheet on the retreating side predominantly was the better speed and weld orientation. Traveling at 20 IPM with the aluminum top sheet on the retreating side of the weld and using the tool with a 0.039” diameter scribe produced the highest failure load at 3.7 kN.

Introduction

Friction stir welding (FSW) is a solid-state welding process that was developed by The Welding Institute in 1991[1, 2]. Solid-state meaning the materials are joined together below their melting points. Compared to traditional fusion welding where materials are melted together, FSW uses a different approach by “stirring” the materials together. A machine with a special tool made up of a shoulder and pin applies a downward forge force, quickly rotates the tool, creating frictional heat to plastically deform the material to a state where it is soft enough to mix. The tool travels linearly along the joint line. The softened materials are stirred from the front of the tool to the back of the tool. A weld is formed behind the tool. The intense plastic deformation produces fine grain sizes, high joint strength, low distortion, and no melt-related defects[3].

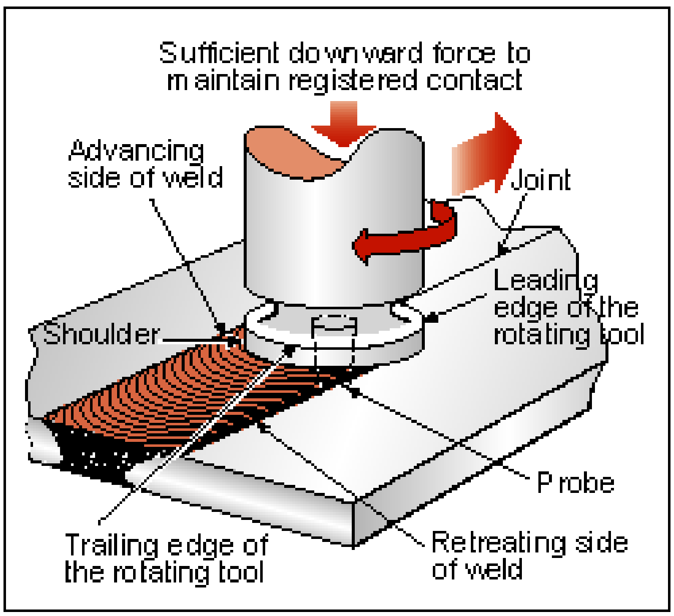


Figure 1: Labeled diagram of friction stir welding[2].

The need to use dissimilar metal joints often comes up in the automotive industry. The joining of aluminum to steel is highly sought. Steel offers great strength, but is heavy. Aluminum's strength is favorable while being light. The joining of these two dissimilar metals can offer weight savings in an automotive application thus reducing fuel consumption, and increasing the performance of vehicles. The joining of aluminum and steel can be a challenging task by conventional fusion welding techniques. The high difference between each material's melting points make it nearly impossible to weld without melting the aluminum, (melting point of Al is 660 °C and iron is 1533°C, iron being a constituent of steel)[4]. Also the development of intermetallic compounds (IMC's) in the interface pose a problem when joining aluminum to steel at high temperatures. IMC's have high hardness, but low ductility; they are very brittle materials. The formation of the IMC's can be seen in the iron and aluminum binary phase diagram below. The thickness of the intermetallic layers at the interface have a major effect on the strength of the joint. Bozzi investigated the thickness of IMC's and how they affect lap shear strengths when spot welding Al 6016 and IF-steel. It was found that the IMC's increased strengths. If the IMC layer was too thin or too large the lap shear strength suffered. Bozzi found in his study that about 8 µm was ideal for joint strengths. Bozzi also found that the thickness of the IMC increased as the rotational speed and penetration depth increased[5]. To minimize the thickness and formation of IMC's, less heat input is needed to improve joint strengths. FSW being a solid-state joining technique is a potential candidate for welding aluminum to steel.

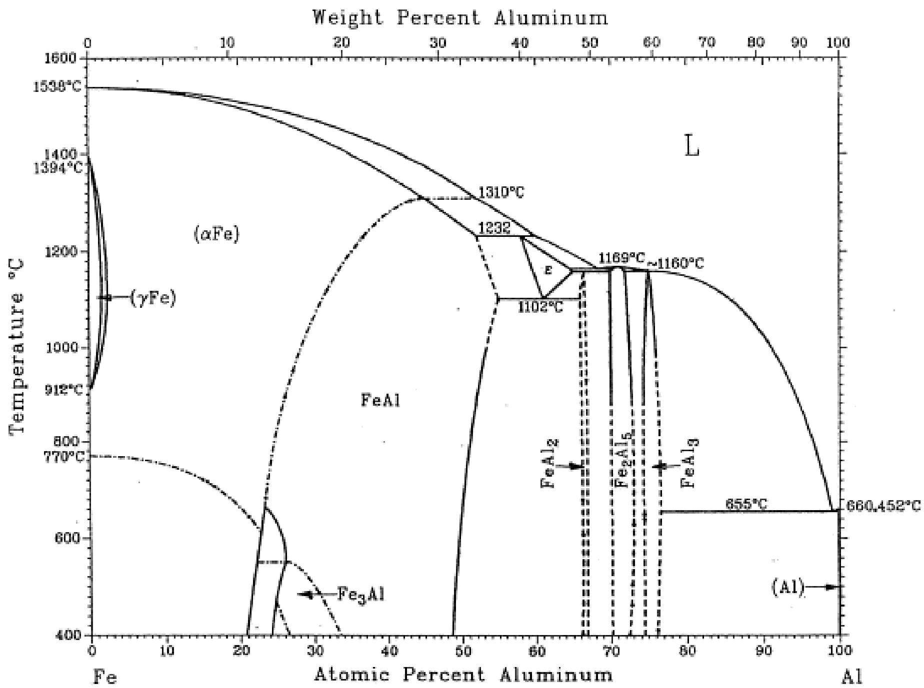


Figure 2: Binary phase diagram of Al-Fe[6].

The main process parameters in FSW are: tool rotational speed, traverse speed, the side at which the tool is advancing or retreating, plunge rate and depth, and tilt angle. Each play a significant role in the resulting strength of the weld. Increasing tool rotation and decreasing travel speed result in more frictional heat. The rate at which you plunge the tool into the material depends on the material thickness and material type. Thicker materials require a longer plunge rate. Traverse speed is the rate at which the tool travels across the joint. The advancing side of the weld is at the side of the tool where the tool's rotation and welding direction are the same. The retreating side is at the side of the tool where the tool's rotation is opposite that of the welding direction.

When lap welding soft-hard materials, how deep you plunge into the hard bottom sheet affects joint strengths. Plunging into the hard material can also result in excessive wearing of the tool. Guifeng Zhang investigated friction stir brazing to reduce the effect of tool wear experienced when working with steel. He used a tool that had no pin and introduced zinc foil as filler material. The tool didn't penetrate the steel sheet; Metallurgical bonding joined the steel and aluminum sheets together[7]. J. T. Xiong, used a tool that incorporated a cutting pin. The cutting pin allowed deeper penetration into the bottom layer while reducing tool wear and resulted in a strong joint with 89.7 MPa[3]. In M. Movahedi's study, the feasibility of friction stir lap welding Al-5083 and aluminum clad steel sheets was investigated. Al-1100 was roll bonded onto the steel to allow the materials to join without the tool having to penetrate the steel layer. It was found that decreasing the thickness of the al-1100 layer resulted in higher joint strengths. Fracture loads reached up to 94% of the St-12 base material[8]

Proper tool material and design have to be considered before welding harder materials. Tool design includes the pin and shoulder diameter. The pin can have different features like: flats, flutes, cutting pin, and spirals. The shoulder design can be concave, spiraled, convex, or stepped. The type of tool design usually depends on the material and joint configuration to be welded.

When working with galvanized steel, one has to look to see if any braze bonding is occurring because of the zinc layer. In studies, it has been shown that when friction stir welding aluminum and steel, the introduction of zinc improves joint strengths[7 9 10]. Guifeng Zhang used zinc foil as filler material to obtain a sound joint[7]. Chen and Nakata compared joint strengths between steels that were zinc-coated and uncoated. The zinc coated steel had a joint strength as high as 97.7% of the steel. The uncoated, brushed finished steel showed a joint strength of 63.2% of the steel[9]. The low melting point of zinc (491 C) causes it to melt during welding joining the aluminum and steel. During friction stir welding, temperatures are above the eutectic point of aluminum and zinc. After welding, when the material is cooling, a eutectic structure is formed aiding in higher bonding strength[10].

The objectives of this study were to determine the feasibility of using a scribe tool to friction stir lap weld 6022 aluminum and low carbon electro galvanized steel alloy sheets, 1.0 mm and 0.7 mm thick respectively. Uncoated steel sheets were tested as well to determine if the zinc layer found in galvanized steel was causing brazing to occur at the interface and increasing the joint strengths of the welds. The materials will be in a lap joint configuration; the aluminum sheet will be placed on top and the steel sheet on bottom. Multiple scribe tools will be tested in the joining of the two dissimilar metals. Optimization of weld parameters (travel speed and the placement of the aluminum on the advancing or retreating side of the weld) will be done to create a weld capable of being used within the automotive industry. Welds will go through metallurgical analysis and mechanical properties evaluation to investigate material flow and any development of intermetallic compounds (IMC's) as well as tensile lap shear strengths. The scribe being tested is made of tungsten carbide in a cobalt matrix and is inserted into the pin of the tool. The scribe is being tested to prevent tool wear in a cost efficient manner.

Table 1: Chemical Composition of 6022 Aluminum alloy (wt. %)[11].

Alloying Element	Chemical Composition Limits (Wt. %)
Si	0.8 - 1.5
Fe	0.05 - 0.20
Cu	0.01 - 0.11
Mn	0.02 - 0.10
Mg	0.45 - 0.70
Cr	0.10
Zn	0.25
Ti	0.15
Others	each 0.05, total 0.15
Aluminum	Remainder

Broader Impact

Success of the scribe tool's effect on the weldability of joining aluminum to steel by friction stir welding would open the doors of the automotive and aerospace industries. The current methods of joining dissimilar metals are by self-piercing rivets, laser brazing, and resistance spot welding. The rivets used add unnecessary weight to its application. Friction stir welding is cleaner than other welding techniques and does not require the use of an argon shield. Friction stir lap welding, being more time and cost efficient can replace the current methods of joining dissimilar metals.

The automotive industry wants to incorporate aluminum into their vehicles' structure and body. Replacing steel with aluminum will decrease the weight of the vehicle resulting in reduced fuel consumption and an increase in performance. Using aluminum alloys will allow the vehicle to retain its strength, but with lighter materials.

The scribe being used will also benefit FSW in whole. When welding hard materials like steel, the material of the tool has to be harder than the material being welded. Tungsten is a very hard material, but it is also expensive. So being able to insert a small scribe made of tungsten rather than producing a tool entirely of tungsten is feasible and cost efficient.

Procedure

The base materials used in this research were 6022 aluminum and low carbon electro galvanized steel alloy panels, 1.0 mm and 0.7 mm thick respectively. For comparison, 2 types of steel panels were used, i.e. (coated and uncoated). The dimensions of the panels were 12.0" x 5.0". A scribe tool was designed for this project. Multiple tools were made, each with different designs. The tool was made of H13 steel and the scribe insert was made of a tungsten carbide in a cobalt matrix. Tool A consisted of a flat shoulder having a diameter of 0.365", a cylindrical pin with 0.158" diameter, 0.036" length, and the scribe 0.059" diameter, and 0.010"length. The center of the scribe was offset from the center of the pin by 0.045". Each tool has the same shoulder and pin dimensions, but different diameter scribes, distance from the center of the pin to the center of the scribe, and the number of scribes inserted in the pin. Tool B used a scribe with a diameter of 0.039" and was offset 0.030". Tool C had two scribes, each with a diameter of 0.050". They were placed 180 degrees apart from each other and each offset from the center of the pin 0.045". The idea behind using a scribe is the ability to be able to plunge through the aluminum, the pin will remain flush with the surface of the steel, and the scribe will enter into the steel gouging the steel, allowing aluminum to fill the voids thus creating a sound joint. The scribe feature was used to promote more mechanical interlocking between the aluminum and steel.

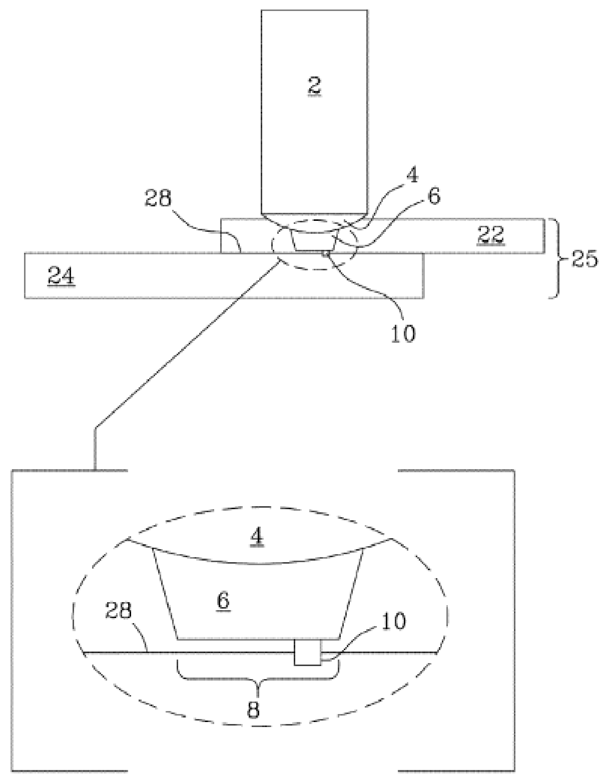
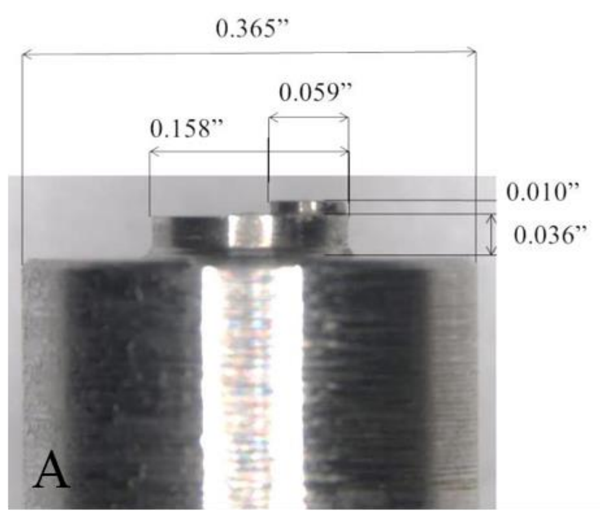
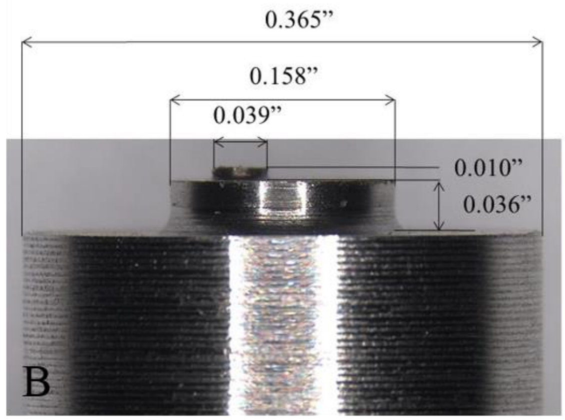


Figure 3: Diagram of weld with scribe tool[12].





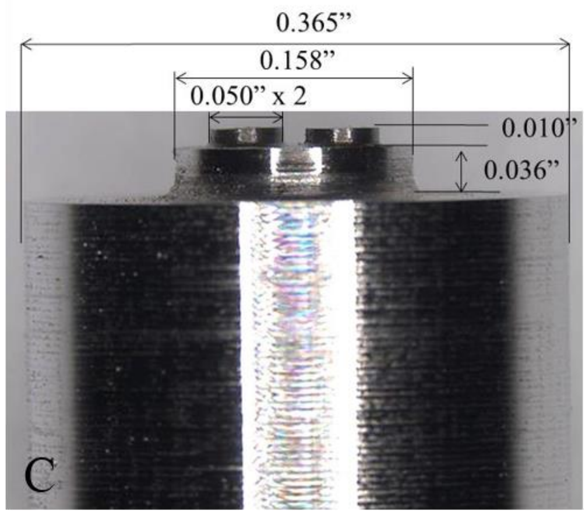


Figure 4: Tools A-C dimensions A) 0.059" scribe diameter B) 0.039" scribe diameter C) 0.050" scribe diameter x 2.

The panels were placed in a lap joint configuration with the aluminum on top and the steel on bottom. There was a one inch overlap. The panels were then friction stir lap welded with the MTS-istir-10 welding machine in the Advanced Materials Processing and Joining (AMP) Lab at the South Dakota School of Mines and Technology. The parameters of the welds were 800 RPM rotational speed, 0° tilt angle, position control, the travel speed varied between 20 and 30 inches per minute (IPM), and alternated the advancing and retreating sides of the weld. Each set of parameters were used with each tool design to make aluminum to steel welds and aluminum to aluminum welds. The aluminum to aluminum welds were used to set a benchmark for tensile lap shear strengths that we wanted to achieve with the aluminum to steel welds. General Motors strength requirements were the weaker of the two metals joined together. The weaker of the two is aluminum so lap shear strengths should be equivalent to 1.0 mm aluminum welded to a 1.0 mm aluminum panel. Tool A was used to weld aluminum to uncoated steel for comparison purposes.

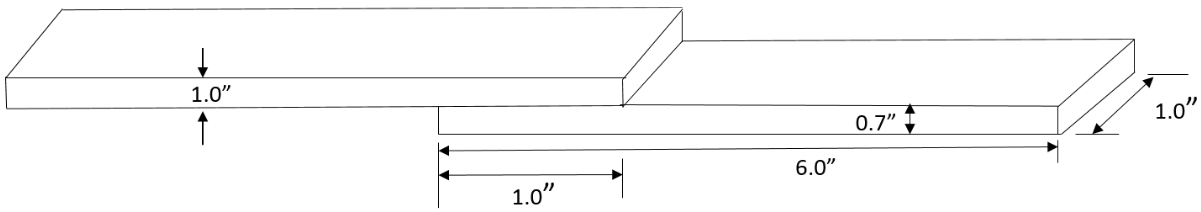


Figure 5: Tensile sample dimensions.

After the welds were produced, two samples were made for microstructural characterization and seven 6.0” X 1.0” samples were made for tensile testing. The samples were cut perpendicular to the weld with a Maxiem 1530 Jet Cutting Center Water Jet.

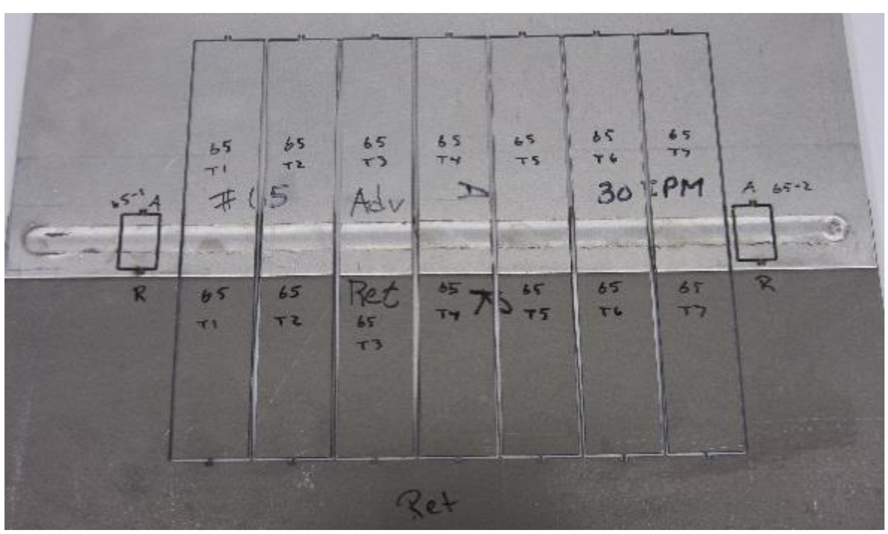


Figure 6: Weld with tensile and microstructural analysis samples cut by water jet.

After the samples were cut, they were hot mounted with a hot mounting press in fine bake lite powder with a cycle of 10 minutes heating and 10 minutes cooling. Mounted samples were rough polished with 240, 320, 400, 600, 1200 grit paper. The final polishing was done with 9, 6, 3, 1, and 0.5 micron diamond suspension on lecloth. The samples were then cleaned with soap and water then isopropyl alcohol. Various etchants were used. 3% Nital solution was used to etch the steel. Nital was swabbed onto the steel for 10-15 seconds. Poulton's reagent was used to etch the aluminum and was swabbed for 2 seconds. The samples were then cleaned again with water and then isopropyl alcohol.

Once etched, macrographs were taken with a Leica Z16 APO Macroscope and micrographs taken with a Nikon Epiphot 200. A Zeiss Supra 40vp SEM (scanning electron microscope) with an EDS (energy dispersive spectrometry) attachment was used to acquire high magnification images and determine if any formation of intermetallic compounds were occurring. The SEM was also used to see if the zinc layer on the galvanized steel was creating a braze bond.

Mechanical properties of the joint were evaluated by tensile lap shear testing. Tensile testing was done on a MTS 858 Mini Bionix 2 using a 55 KN load cell. Dimension of the samples are 1.0" wide and 6.0" long. All tests were conducted at a constant cross-head displacement rate of 0.1". Seven specimens were tested and the maximum loads were averaged.

Results

Welds had the option of being done in position control and force control. Position control allows you to set the friction stir welder to a set depth that the machine will maintain and follow as a guideline as it welds down the joint line. Force control operates with a constant amount of downward force that is applied. Figure 7 shows Welds 57-61 made using 700-800 lbs. of force. Trials with force control were inconsistent. The sheets being so thin didn't leave much room for error when in force control. The tool would move up and down as it traveled down the weld line, going through the bottom sheet or coming up too high so gaps were visible at the top of the weld due to the decrease in plunge depth.

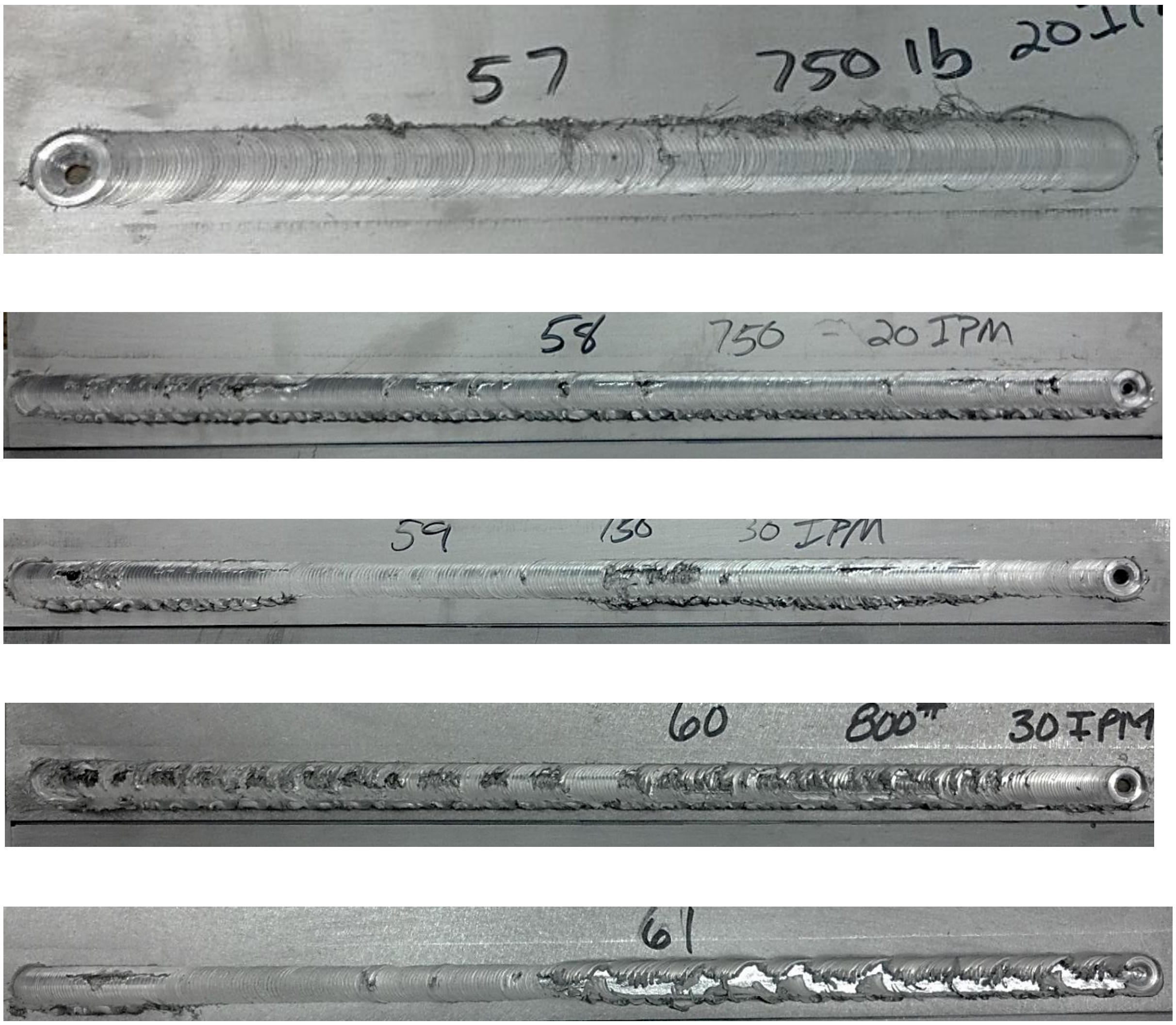


Figure 7: Welds 57-61 made using force control. Weld 57) 750 lbf. 20 IPM. 58) 750 lbf. 20 IPM. 59) 750 lbf. 30 IPM. 60) 800 lbf. 30 IPM 61) 700 lbf. 30 IPM .

After welding, it was noticed that steel would build up on the tool as can be seen in figure 8 . This may have increased the plunge depth of some of the welds. To remove the steel build up, aluminum to aluminum welds were made.

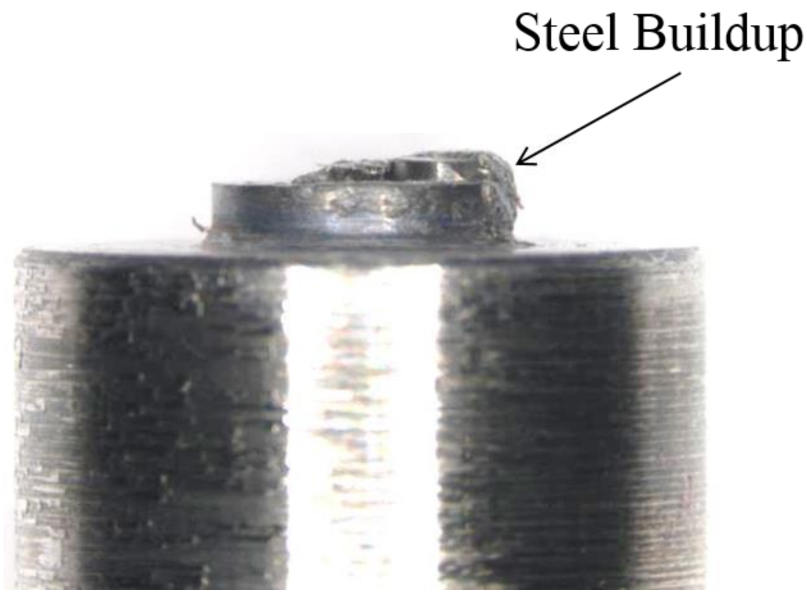


Figure 8: Tool with steel build up after welds.

Table 2. Shows the average failure loads of the welds made with tool A and coated steel. The table also shows aluminum to aluminum welds that were made with tool A. General Motors would like tensile strengths to be as high as the weakest material within the stack of materials being used, if the weakest material were welded to itself. The weakest material is aluminum. The aluminum to aluminum weld strengths are the benchmark we are trying to achieve. The rotational speed was set at 800 RPM, tilt angle at 0°, the plunge depth was the length of the pin plus scribe (0.046”), the advancing and retreating sides alternated, and the travel speed varied from 20-30 IPM. From the table, the failure load of the weld was higher when the travel speed was 20 IPM compared to 30 IPM. This was the same when comparing travel speeds along with alternating the advancing and retreating side of the weld. When the aluminum

top sheet was on the retreating side during tensile testing, the failure load also increased significantly compared to the retreating side being on the steel side. This was true for both travel speeds.

Table 2: The average failure loads of the welds made with tool A and coated steel.

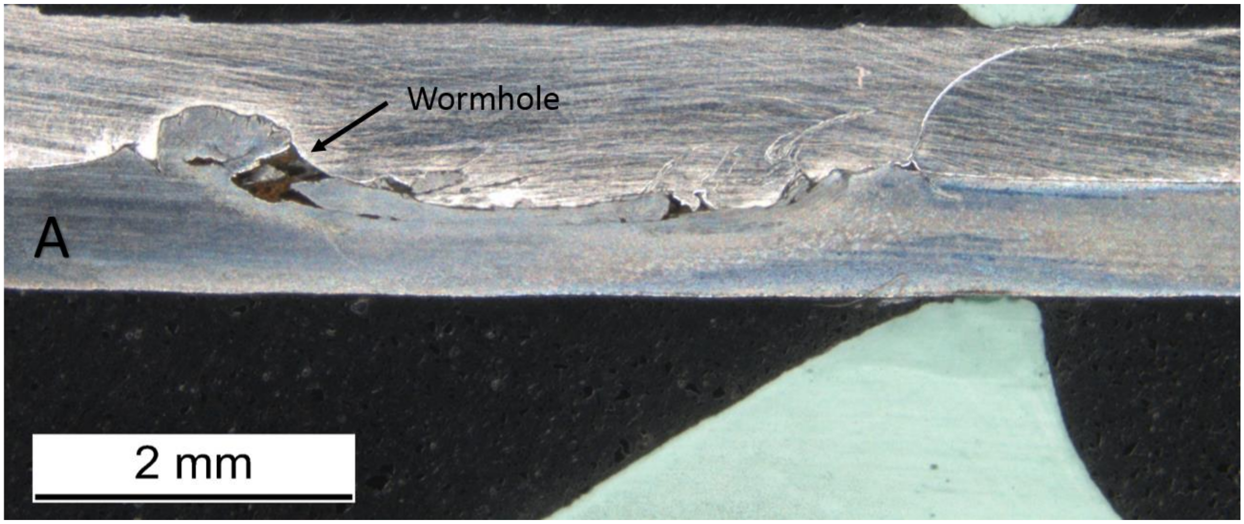
Weld #	Materials	Advancing or Retreating	Travel Speed	Average Failure Load	
64	Al-Steel	Al-Advancing	20	588.6 lbf± 29.5	2.6kN ± 0.13
65	Al-Steel	Al-Advancing	30	547.4 lbf ± 79.6	2.4 kN ± 0.35
66	Al-Steel	Al-Retreating	20	819.1 lbf ± 80.2	3.6 kN ± 0.36
67	Al-Steel	Al-Retreating	30	732.7 lbf ± 43.0	3.3 kN ± 0.19
68	Al-Al	Al-Top Sheet Retreating	20	953.7 lbf ± 39.5	4.2 kN ± 0.17
69	Al-Al	Al-Top Sheet Retreating	30	977.1 lbf ± 46.1	4.3kN ± 0.2
70	Al-Al	Al-Top Sheet Advancing	20	1028.9 lbf ± 12.0	4.6 kN ± 0.05
71	Al-Al	Al-Top Sheet Advancing	30	1030.7 lbf ± 4.9	4.6 kN ± 0.02

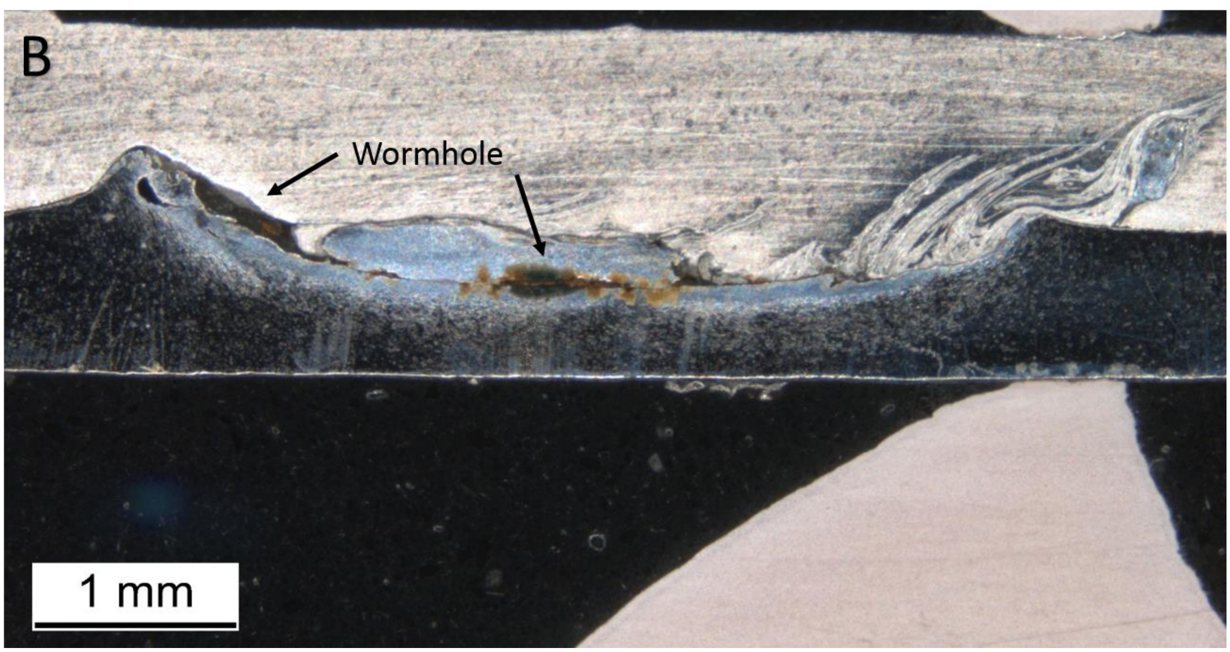
Table 3. Shows the average failure loads of the welds made with tool A and uncoated steel. From the table, you can see that the travel speed impacted the failure load of the weld the most when working with the uncoated steel. For both types of weld geometry it can be seen 30 IPM produces the higher failure loads. When comparing the advancing side being on the aluminum side with the retreating side being on the aluminum side of the weld, there isn’t much of a difference in the failure loads when looking at each travel speed. When the aluminum top sheet is on the retreating side the failure load is more consistent throughout the weld.

Table 3: Average failure loads of the welds made with tool A and uncoated steel.

Weld #	Materials	Weld Geometry	Travel Speed	Average Failure Load	
72	Al-Uncoated Steel	Al-Advancing	30 IPM	741.9 lbf±89.6	3.3 kN ± 0.40
73	Al-Uncoated Steel	Al-Advancing	20 IPM	635.7 lbf ± 55.8	2.8 kN ± 0.25
74	Al-Uncoated Steel	Al-Retreating	30 IPM	760.3 lbf ± 22.3	3.4 kN ± 0.05
75	Al-Uncoated Steel	Al-Retreating	20 IPM	601 lbf ± 41.3	2.7 kN± 0.18

Comparing the tensile testing results found from welding aluminum to coated steel with the results from aluminum to uncoated steel, we can see that for both types of weld geometry and travel speed, the uncoated produced the highest failure loads, except when the coated steel was welded at 20 IPM with the retreating side on the aluminum side of the weld; that created the highest failure load.


Wormhole
A
2 mm


B
Wormhole
1 mm

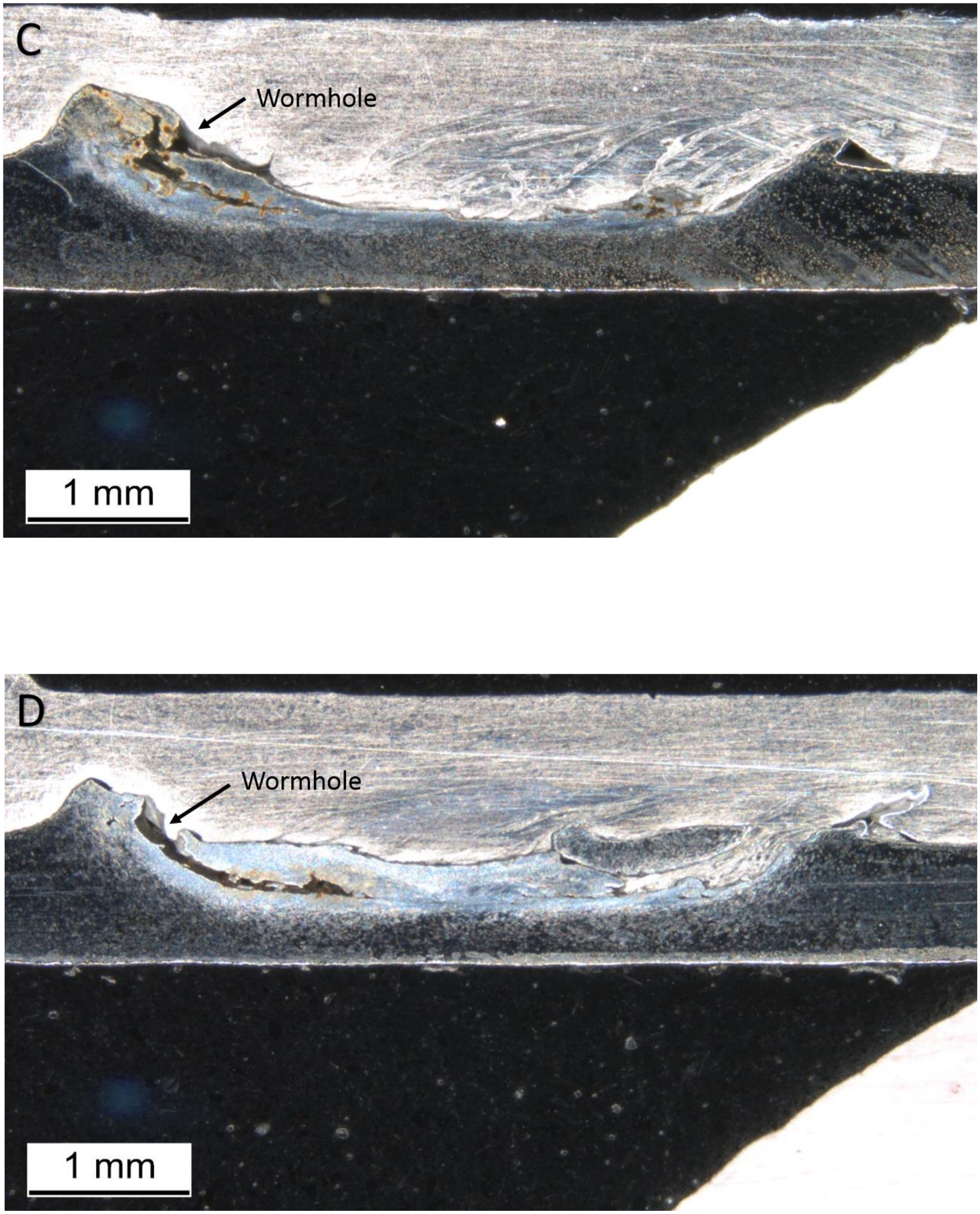
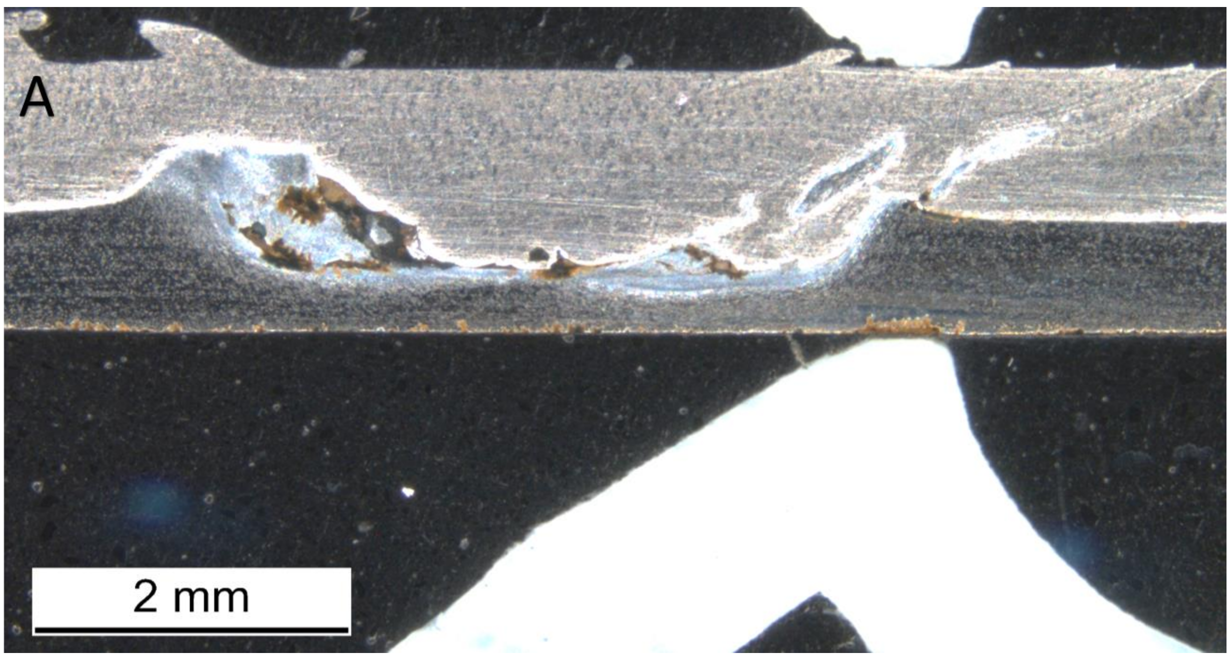
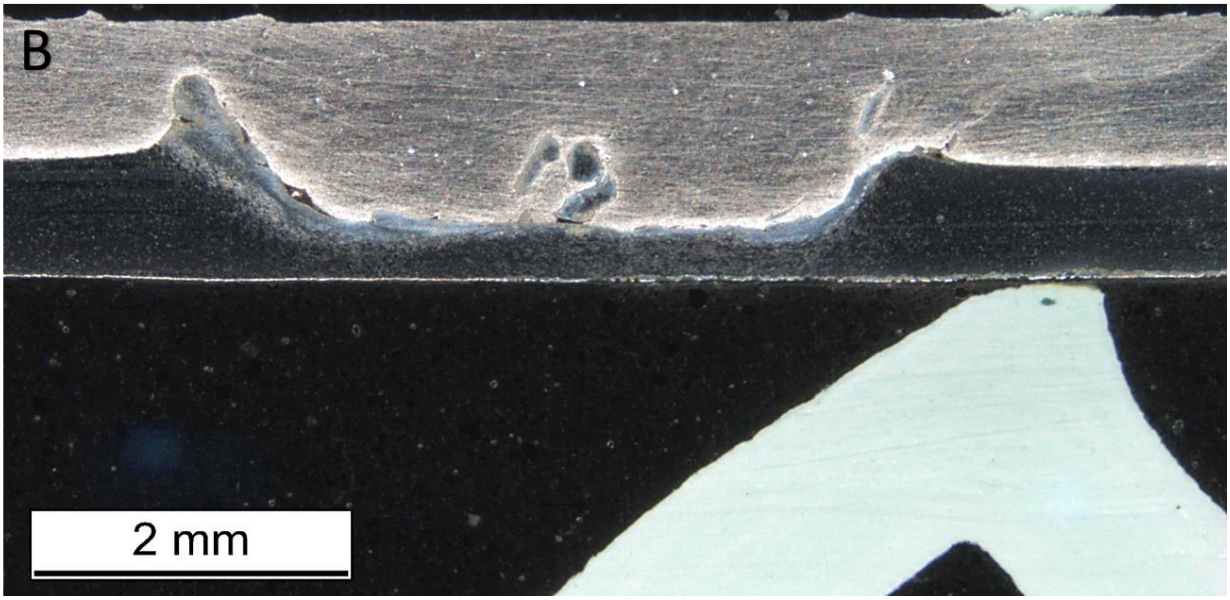


Figure 9: Macrographs of welds 64-67 made with tool A and coated steel. A) weld 64 Aluminum advancing 20 IPM B) weld 65 Aluminum advancing 30 IPM C) weld 66 Aluminum retreating 20 IPM D) weld 67 Aluminum retreating 30 IPM.

Figure 9 shows the macroscopic view of the welds made with tool A and the coated steel for each variation in parameters. It can be seen that the travel speed had a major effect on the flow and mixing of the materials. Wormholes are present in both 20 and 30 IPM travel speeds, but when looking at the two; the amount and size of wormholes increased as the travel speed increased. This may be because at 30 IPM there isn't enough frictional heat being generated so the materials aren't mixing properly. At 20 IPM the wormholes either decrease in size or the number of them present possibly due to more heat being applied at the slower travel speed allowing the material to properly mix.




B
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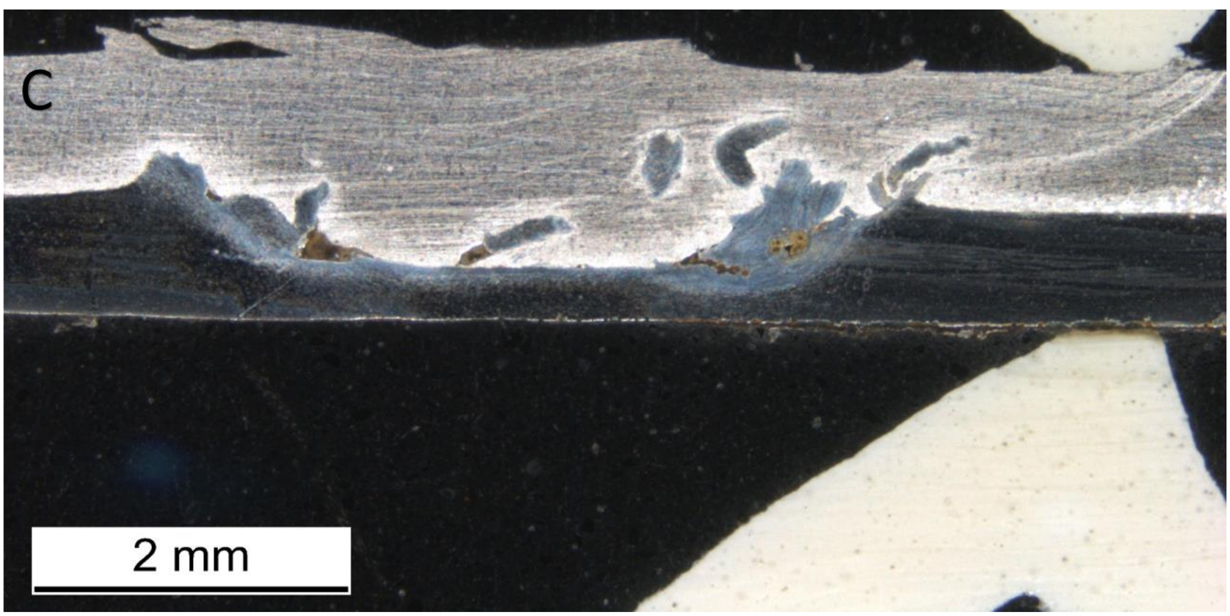
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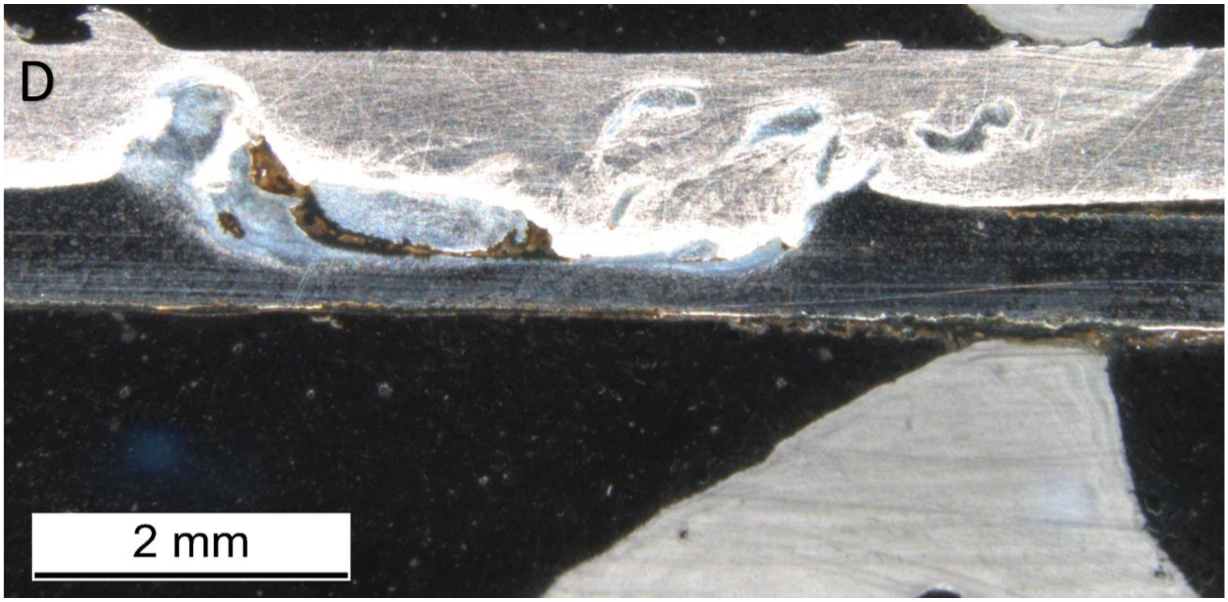
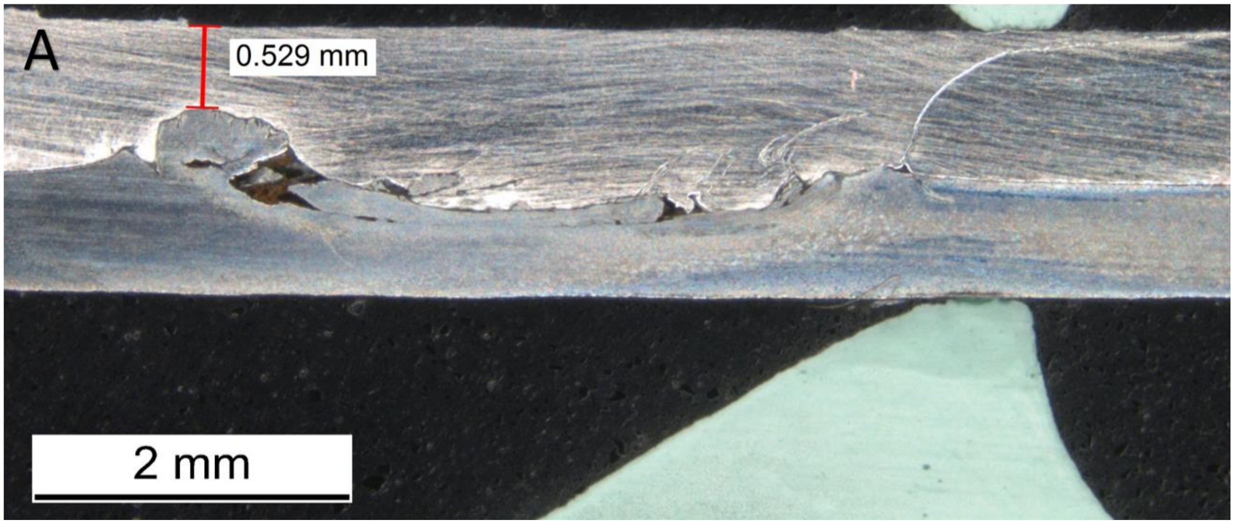
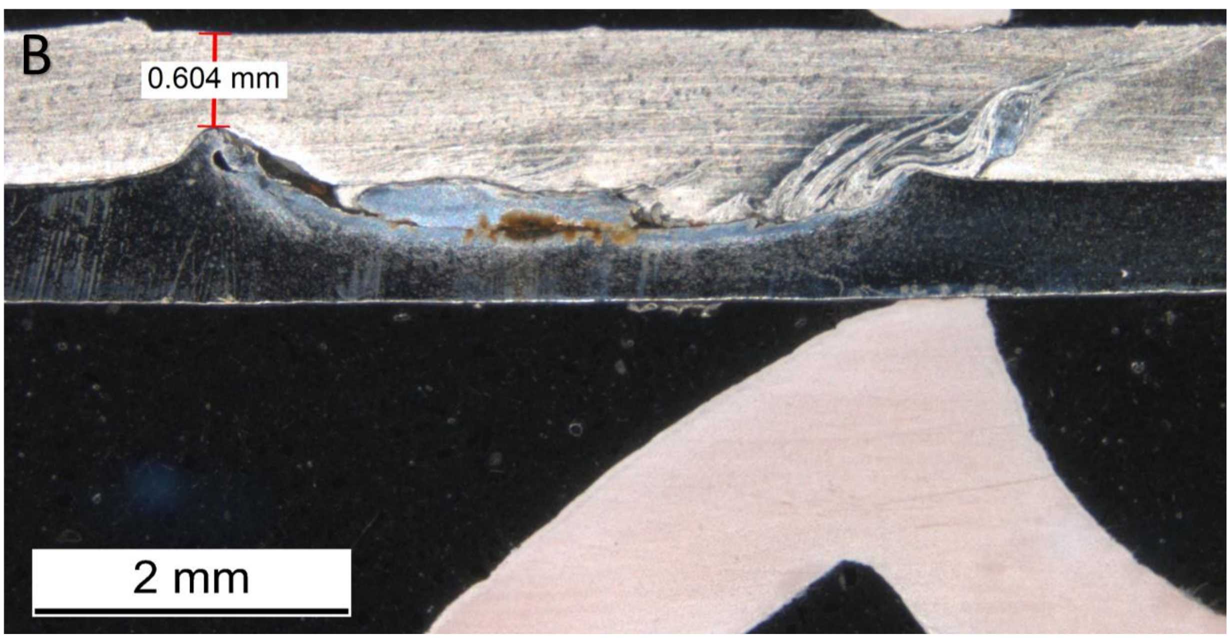
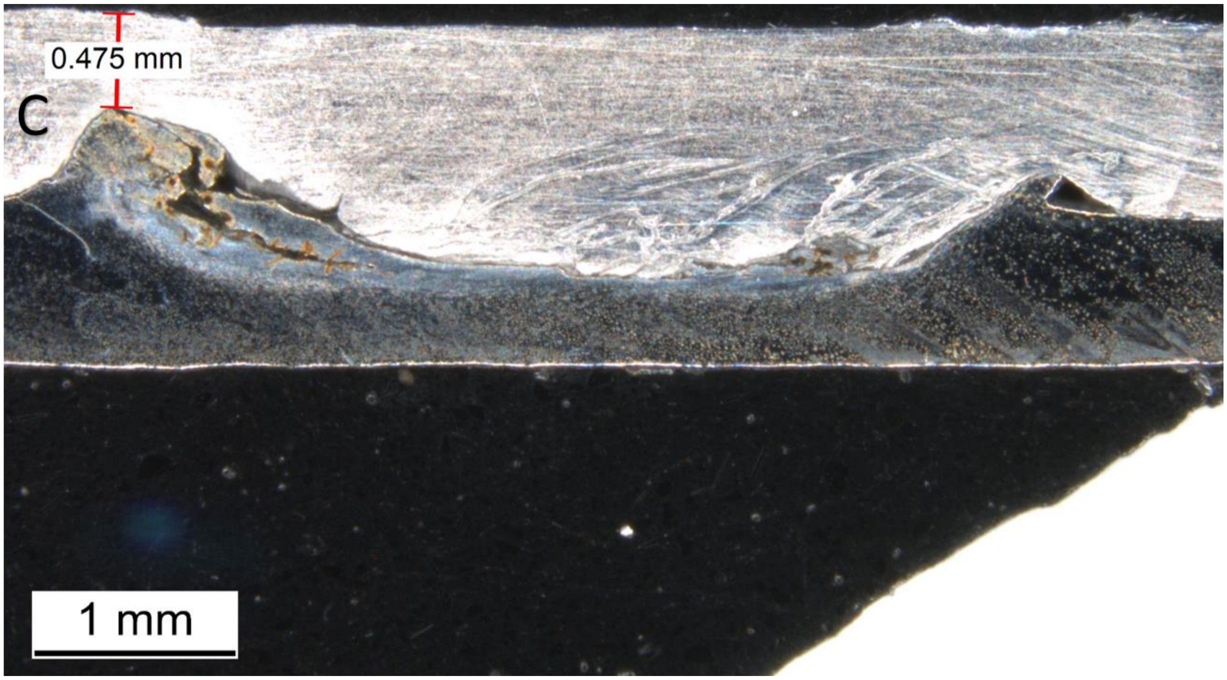


Figure 10: Macrogaphs of welds 72-75 made with tool A and uncoated steel. A) weld 72 Aluminum advancing 30 IPM B) weld 73 Aluminum advancing 20 IPM C) weld 74 Aluminum retreating 30 IPM D) weld 75 Aluminum retreating 20 IPM.

Figure 10 shows the macroscopic views of welds 72-75 made with tool A and the uncoated steel. From the macrographs we can see the travel speed affects the hooking feature's height on the retreating side. The hooking feature increases in size at 20 IPM for both the advancing and retreating side being on the aluminum side of the weld. Compared to the welds done with coated steel, you can see in the uncoated that a lot more steel is being stirred up into the aluminum. There isn't a noticeable trend between parameters that affected the wormhole size as where the coated welds did show a trend. Looking at table 3 and figure 10 there is a correlation between the effective top sheet thickness and joint strength. The welds made at 20 IPM had a much thinner top sheet above the hook on the retreating side and had the weaker strengths. At 30 IPM the hooks were wider and smaller. They left more of the aluminum top sheet above the hook. This is presumed to have increased the weld strengths.


A
0.529 mm
2 mm


B
0.604 mm
2 mm



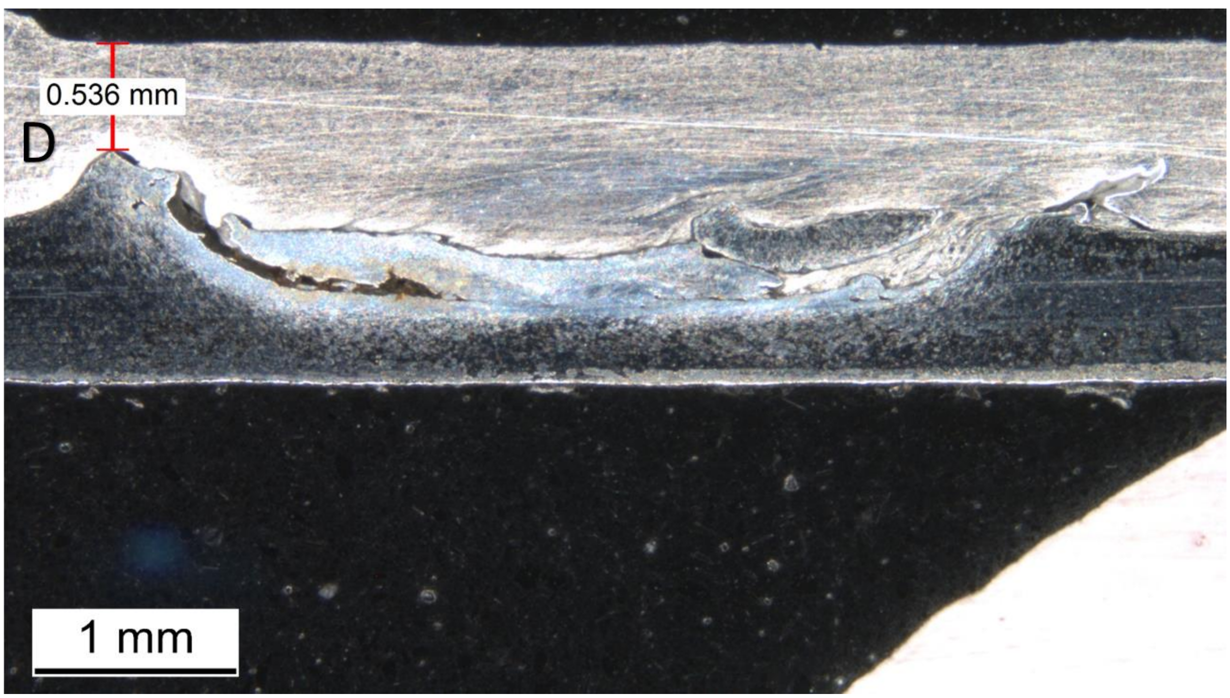
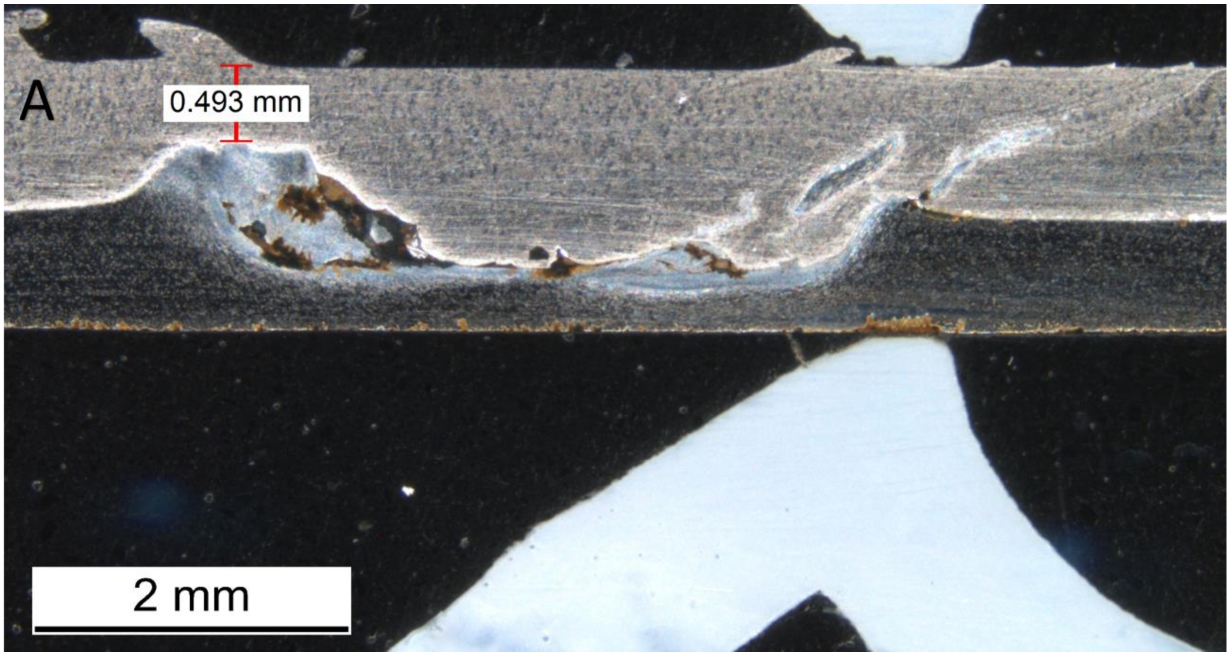
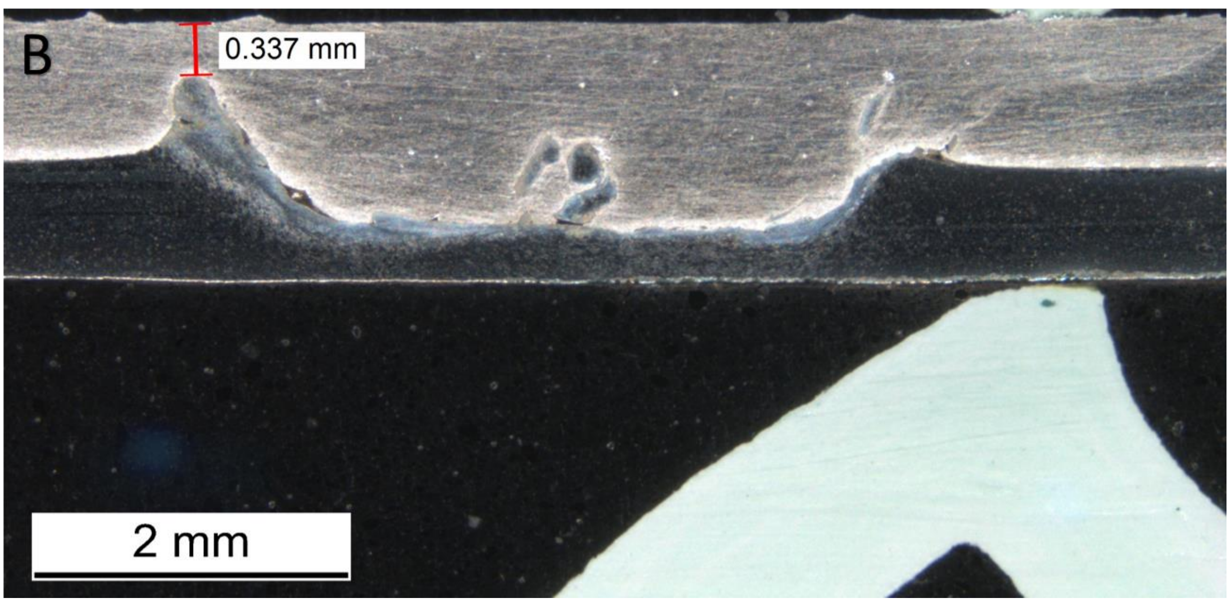


Figure 11: Measurements of effective sheet thickness, weld 64-67 made with tool A and coated steel. A) weld 64 Aluminum advancing 20 IPM B) weld 65 Aluminum advancing 30 IPM C) weld 66 Aluminum retreating 20 IPM D) weld 67 Aluminum retreating 30 IPM.

Figure 11 shows the macroscopic view of welds 64-67 made with tool A and coated steel along with thickness measurements of the aluminum top sheet above the hooking feature on the retreating side. The measurement of the aluminum thickness above the hooking feature was made with the Leica Z16 APO macroscope using a Las Vf41 program with measuring capabilities. The thickness of the aluminum top-sheet decreased as you went from 30 IPM to 20 IPM. This occurred for both the advancing and retreating side being on the aluminum side of the weld. At 20 IPM, when the aluminum was on the retreating side of the weld, there was a thinner aluminum top sheet. This can be said for the travel speed of 30 IPM as well. Looking at table 2 and figure 11, the welds made at 30 IPM had a thicker aluminum top sheet above the hooking feature compared to the welds at 20 IPM, but there was a difference in the shape of the hook. At 30 IPM the hooking feature on the retreating side was narrow and came to a point at the top. Welding at 20 IPM, the hooking feature on the retreating side was wider and the top of the hook was flatter and had a larger surface area. The failure load was higher for the 20 IPM welds with the thin effective top sheet and blunt shaped hook. The flatter and more surface area the hook had on top while not reducing the aluminum top sheet thickness allowed the stress from the tensile testing to be able to distribute over a large area as compared to having a lot of stress at one point.


A
0.493 mm
2 mm


B
0.337 mm
2 mm

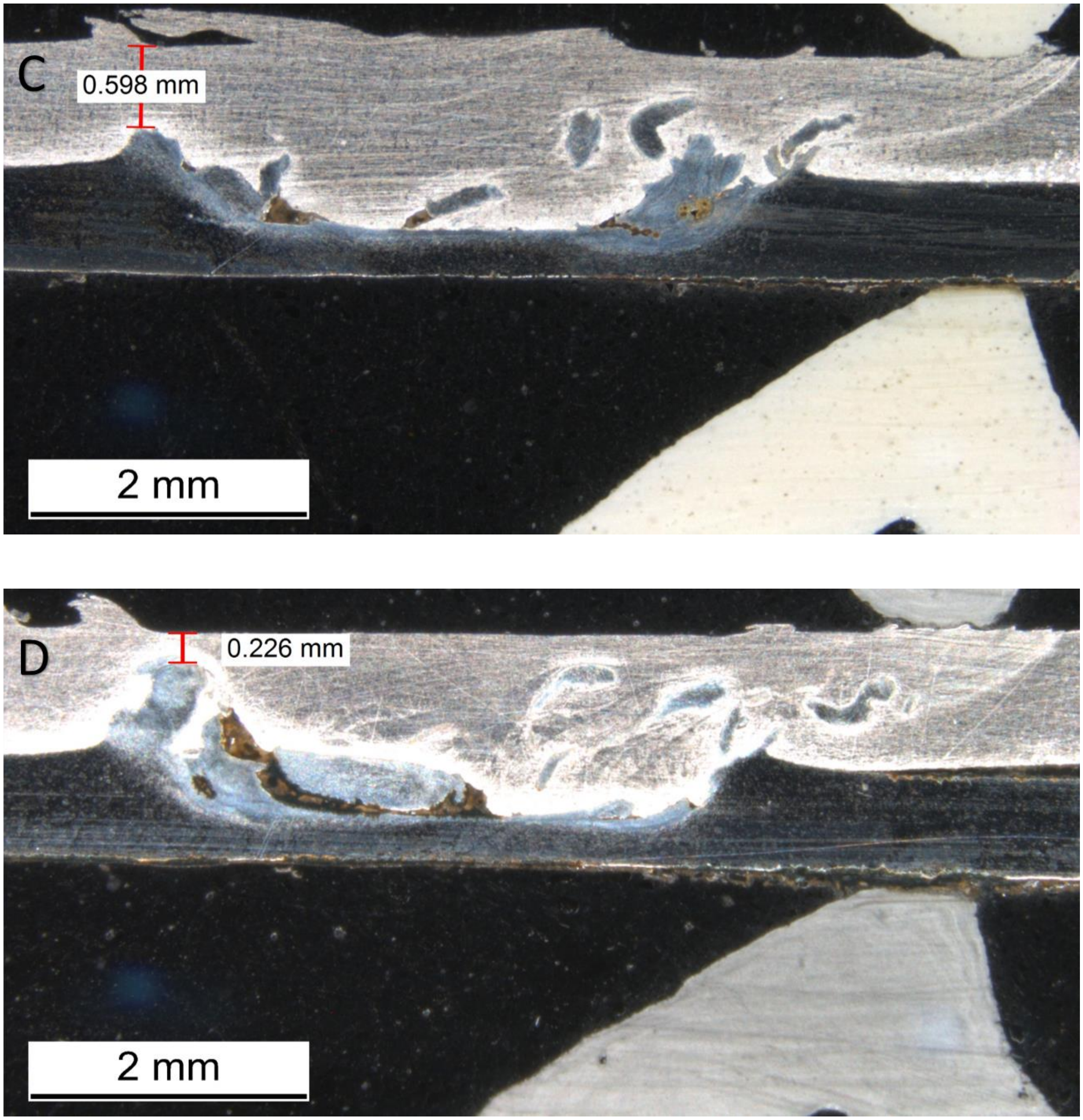


Figure 12: Macrographs of welds 72-75 made with tool A and uncoated steel. A) weld 72 Aluminum advancing 30 IPM B) weld 73 Aluminum advancing 20 IPM C) weld 74 Aluminum retreating 30 IPM D) weld 75 Aluminum retreating 20 IPM.

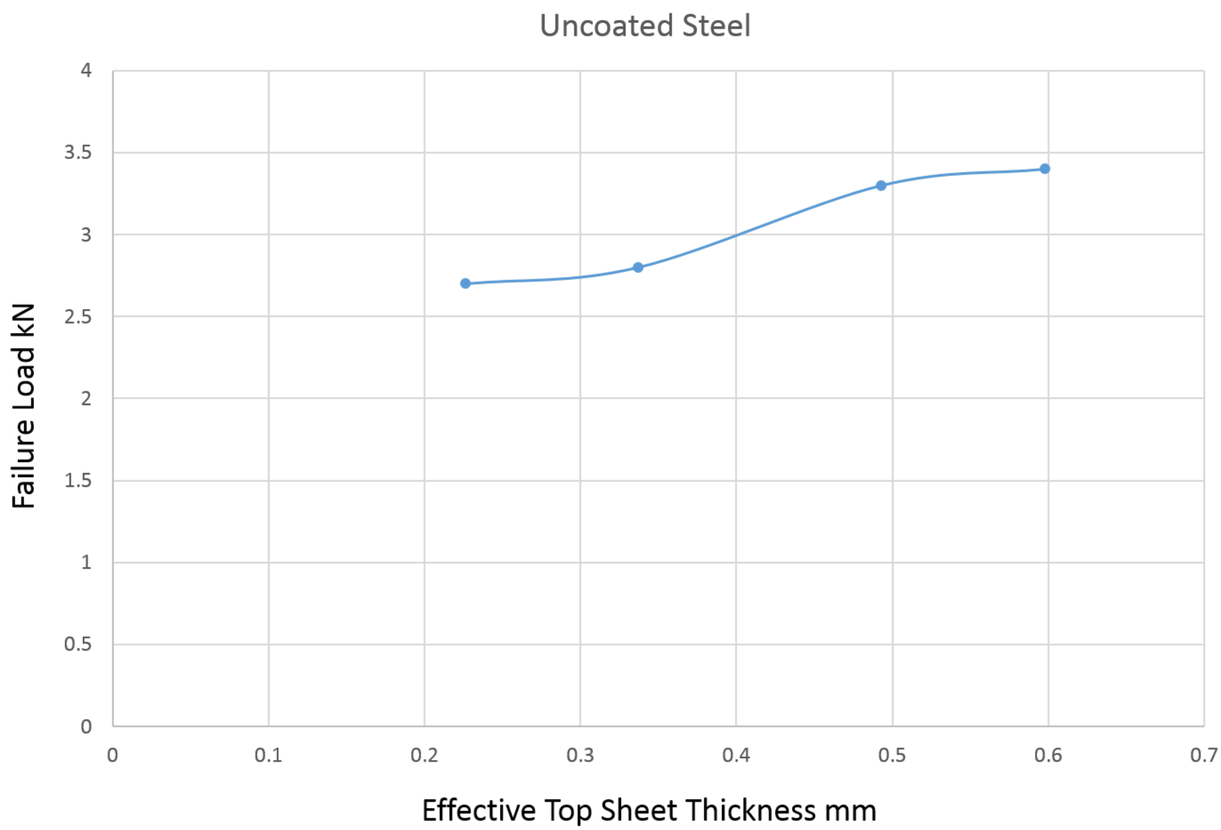


Figure 13: Chart comparing the average failure load to the effective top sheet of aluminum of welds 72-75.

Figure 12 shows the macroscopic view of welds 72-75 made with tool A and uncoated steel along with thickness measurements of the aluminum top sheet above the hooking feature on the retreating side. It can be seen with both orientations of the advancing and retreating side that the aluminum top sheet thickness declines as the travel speed decreases from 30 IPM to 20 IPM. At 30 IPM, when the aluminum is on the retreating side of the weld, the thickness of the aluminum top sheet is thicker than when the advancing side is on the aluminum side. This is opposite of the results at 20 IPM and alternating the advancing and retreating sides of the weld. In figure 13, the average failure loads of the welds and the effective top sheet thickness about the hooking feature were looked at to see if there were any correlation between the two. Figure 13 shows a rise in the failure load as the aluminum top sheet thickness increased.

Table 4: Average failure loads and parameters of welds 79-86 made with tool B.

Weld #	Materials	Weld Geometry	Travel Speed	Average Failure Load	
79	Al-Steel	Al-Retreating	20	841.9 lbf ± 213.1	3.7kN ± 0.9
80	Al-Steel	Al-Retreating	30	703.3 lbf ± 148.9	3.1kN ± 0.6
81	Al-Steel	Al-Advancing	20	768.9 lbf ± 39.0	3.4kN ± 0.2
82	Al-Steel	Al-Advancing	30	769.5 lbf ± 219.7	3.4kN ± 1.0
83	Al-Al	Al-Top Sheet Advancing	20	956.6 lbf ± 72.1	4.3kN ± 0.3
84	Al-Al	Al-Top Sheet Advancing	30	962.0 lbf ± 60.7	4.3kN ± 0.3
85	Al-Al	Al-Top Sheet Retreating	20	1187.5 lbf ± 57.8	5.3kN ± 0.2
86	Al-Al	Al-Top Sheet Retreating	30	1086.3 lbf ± 44.2	4.8kN ± 0.2

Table 4 shows the averaged failure loads of the welds made with tool B. When looking at travel speed, 20 IPM creates the welds with the highest or most consistent failure loads for both types of weld geometry. The decrease in speed creates more frictional heat allowing more material flow around the tool, filling in the voids left behind the tool thus creating a better weld. Using tool B with the parameters 20 IPM and the retreating side on the aluminum side of the weld produced the highest average failure load out of the other tools and parameters. When alternating between the advancing and retreating side of the weld, having the retreating side be on the aluminum side and traveling at 20 IPM creates the highest failure load. At 30 IPM and the same weld orientation the weakest weld was made. Having the aluminum be on the advancing side of the weld, the average failures were about the same, but traveling at 20 IPM was more consistent throughout the weld.

Table 5: Average failure loads and parameters of welds 99-106 made with tool C.

Weld #	Materials	Weld Geometry	Travel Speed	Average Failure Load	
99	Al-Steel	Al-Retreating	20	724.8 lbf ± 197.5	3.2 kN ± 0.9
100	Al-Steel	Al-Retreating	30	815.7 lbf ± 133.2	3.6 kN ± 0.6
101	Al-Al	Al-Top Sheet Retreating	20	931.7 lbf ± 12.1	4.1 kN ± 0.1
102	Al-Al	Al-Top Sheet Retreating	30	921.8 lbf ± 18.0	4.1 kN ± 0.1
103	Al-Al	Al-Advancing	20	461.3 lbf ± 74.4	2.1 kN ± 0.3
104	Al-Al	Al-Advancing	30	641.9 lbf ± 152.7	2.9 kN ± 0.7
105	Al-Al	Al-Top Sheet Advancing	20	820.0 lbf ± 75.2	3.6 kN ± 0.3
106	Al-Al	Al-Top Sheet Advancing	30	902.5 lbf ± 46.9	4.0 kN ± 0.2

Table 5 shows the welds made with tool C and coated steel. When looking at failure loads and joint strengths, you can see that 30 IPM produced higher values than the 20 IPM welds. This finding is different when comparing the welds made with tool A and B. When the aluminum panel was on the retreating side of the weld, failure loads were the strongest for both travel speeds.

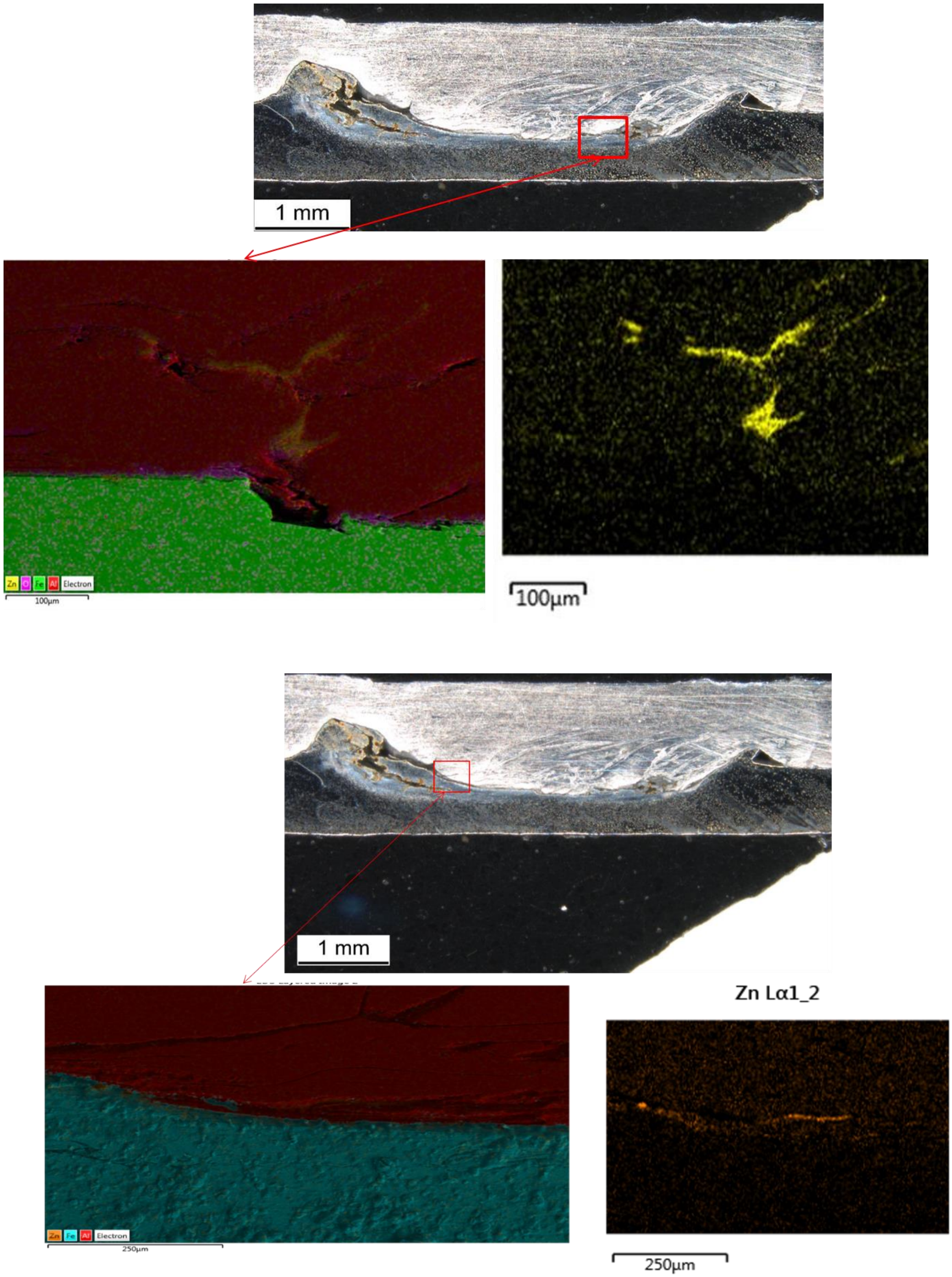


Figure 14: EDS images taken at different locations on the interface of weld 66 using a SEM.

Figure 14 shows preliminary SEM and EDS images. The weld interface was looked at to see if any IMC's were developing or if any brazing was occurring due to the electro-galvanized steel's zinc layer. It was difficult to see if an IMC was present, but referring to Bozzi's findings; an IMC formation may be found at the hooking features where we didn't look[5]. In the EDS it was seen that in a few locations that the zinc was being stirred up into the aluminum. In one location there was a very thin layer of zinc at the interface. A more thorough investigation will be underway in the future.

Figure 15: Weld showing excess amount of flash.

It was noticed that for each weld no matter the parameters there was an excess amount of flash created. This is not good for the automotive industry as it would add in an unnecessary step of removing the flash to achieve a flush finish ready for painting. A change in parameters should be looked into to eliminate any flash.

Discussion

Using a scribe tool to friction stir lap weld aluminum to steel can be a promising innovation in the automotive industry after the parameters are fine tuned. When welding with tool A having the largest scribe produced a weld that had a failure load up to 3.6 kN. It was seen that 20 IPM produced higher failure loads than the welds made at 30 IPM. This may be due to more frictional heat being made at the slower speed allowing the material to properly mix. It can be seen in figure 9 that when the speed decreased the amount and size of wormholes decreased as well. It can be noted that alternating the advancing and retreating side of the weld can affect the joint strength considerably. At 20 IPM, comparing when the aluminum was on the advancing or retreating side, the failure load went from 2.6 kN on the advancing side up to 3.6 kN when the aluminum was on the retreating side.

The size and shape of the hooking features along with the aluminum top sheet thickness played a key role in the strengths of the weld. If the thickness of the top sheet was too thin the failure load during tensile testing was low. When the height of the hook was low and the shape of it was dull and not so much at a point, the failure loads were observed to be high.

Using tool B (smallest scribe diameter) when the aluminum was on the advancing side and changing the travel speed didn’t show much of a difference in the failure loads. At 20 IPM, the failure loads were more consistent throughout the weld than the 30 IPM weld. Comparing the travel speed when the aluminum was on the retreating side of the weld showed that 20 IPM makes a better weld than at 30 IPM. Welding with tool B at 20 IPM and the aluminum on the retreating side made a weld with the highest failure load observed throughout the entire study (3.7 kN). Comparing the joint strengths of the weld when alternating the advancing and retreating side show that at 20 IPM having the aluminum on the retreating side is the best. At 30 IPM it is opposite of that.

Tool C introduced two scribes in the pin. The extra pin may have caused more frictional heat and mixing so it was seen that 30 IPM made better welds than traveling at 20 IPM. This may be a good design to work with as it would be able to make strong welds at faster speeds. Higher failure loads were seen when the aluminum was on the retreating side of the weld.

Tool B outperformed the other tools for most parameters when it came to weld strength. It was hard to say with the mixed strength results whether one tool was superior to the other. Tool B did create the weld with the highest failure load.

Conclusion

Summary

In this study, the feasibility of FSLW aluminum to steel panels with a scribe tool was investigated. The testing of multiple parameters and tool designs was conducted to see how they affected the microstructural and mechanical properties. The scribe tool was capable of making welds, but had not reached the strengths that GM would like to see. Tool B with the smallest scribe diameter made the strongest weld with a failure load of 3.7 kN. The parameters 20 IPM and having the aluminum on the retreating side predominantly gave the higher failure loads. The size and shape of the hooking features also played a role on the joint strengths achieved. The smaller dull hooking features that could distribute the stress from tensile testing over a larger surface area aided in strength values.

Future Work

Recommendations for future work are to experiment with weld parameters to increase weld strengths, reduce the size of the hooking features, and eliminate any flash. More work should be done to characterize the welds at the different parameters. A deeper look at the weld interface should be conducted with a SEM to see if any intermetallic compounds are developing. Also a look at the interface to see if the electro-galvanized steel's zinc layer is causing any braze bonding to occur. GM would like T-peel tests to be done so T-peel testing should be completed to test the welds' adhesive strength. The analysis of the failure locations should be investigated to see where and why the welds are failing to try to prevent these failures as well as to improve the weld strengths.

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